Assessment of the Summertime Thermal Performance of Natural, Zonal Mixed-Mode and Mechanical Ventilation Strategies in Newly-Built BSF Schools Under UKCIP02 Warming Scenarios and the Efficacy of Potential Adaptation Strategies

A dissertation submitted in part fulfilment of the degree of Master of Science Built Environment: Environmental Design and Engineering

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Contents

Abstract

This study investigated three newly-built Central London schools, as part of the *Building Schools for the Future* programme, that employed natural, zonal mixed-mode, and mechanical ventilation strategies for the provision of pollutant expulsion and thermal comfort. The operations of the respective ventilation strategies were modelled for summertime overheating, as defined by *Building Bulletin 101: Ventilation of School Buildings* (BB101), using thermal analysis software (TAS) in a 'medium-high' climate change scenario developed by the *United Kingdom Climate Impacts Programme 2002* (UKCIP02).

The rigour of the designed ventilation strategies were assessed in the warming scenario for the present day, the 2020s, 2050s and 2080s and the points at which they failed were identified. Other ventilation strategies were then devised and modelled to assess the possible adaptations that could be made to the existing situation for the alleviation of summertime overheating.

It was determined that the use of cross-ventilation and split-duct systems, in conjunction with night cooling could prolong natural ventilation strategies till at least the 2050s without significant overheating. Furthermore, classroom geometry was also determined to have an effect on summertime thermal performance. Beyond the 2050s, comfort cooling was recommended as a low-energy hybrid solution to cope with increasing external temperatures, in line with the 'medium-high' warming scenario.

13,814 words

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CHAPTER ONE
Introduction

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Preamble

Environmental design in schools has been considered for at least the past 100 years where Victoria-era schools were designed with features such as high ceilings for the convection of gas from lamps, and the *limiting* of daylight to prevent distraction of pupils. Since then, environmental design in schools has focused on a broader picture other than pupil performance to encompass building energy consumption, space modularity and use flexibility as well as the fostering of an academic and social environment.

Building Schools for the Future

The field of environmental school design has developed considerably with the present Building Schools for the Future (BSF) programme which seeks to build and operate a new generation of schools with energy efficiency in mind, given that 7% of energy consumption in the UK is attributable to public buildings (*DTI*, 2005). Under BSF, the Government plans to increase capital investment to a potential £46 billion over the next 15 years (*House of Commons Education and Skills Committee*, 2007). This will aims to redress the problems of stale environments and inadequate environmental design by embodying current societal values of sustainability, with efficient building design from the point of view of architects and engineers. Furthermore, the investment will also allow the new generation of schools to be demonstrated as sustainable flagships in their communities, in which they are conjectured to take a more significant role, with out-of-hours learning classes, access to sports facilities and the like.

Regulatory Framework

In addition, the global context of this is such; current predictions suggest that the Earth's climate is warming and will continue to warm at a rate that is dependent on the extent of intervention measures (*IPCC*, 2007). This uncertainty is conveyed in the *Special Report on Emissions Scenarios* which forecasts four possible warming scenarios until the end of the century, with varying degrees of governmental and societal intervention taken into account. A result of this has been the UK Government's adoption of the *Climate Change Bill* (2006) which seeks to reduce carbon emissions by 60% on 1990 levels by 2050 which was a result of the European Directive on the *Energy Performance of Buildings 2002/91/EC*, itself a result of European-wide ratification of the *Kyoto Protocol* (1997). The *Climate Change Bill* has translated itself into making change in the UK building stock through Building Regulations, which has seen a revision to *Approved Documents L2* (*ADL2*) and *F* (*ADF*). This has been developed upon to create a set of guidelines especially for schools, codified in *Building Bulletin 101* (*BB101*, 2006) which details the methods and targets of ventilation in school buildings.

Ventilation

With the context of a heightened need to adopt energy efficient school design, to pass on the notions of sustainability to the users of the school, and a large-scale capital investment into school infrastructure, the importance of environmental design in schools is palpable.

An aspect of low-energy design of teaching spaces are the ventilation methods necessary for the provision of health, through pollutant control, and thermal comfort, through the dispelling of resultant heat gains. *Approved Document F* (*ADF*) outlines that ventilation can be facilitated by natural, mechanical or hybrid means.

CIBSE AM10 outlines four main methods of natural ventilation;

- **single-sided single-opening** where the predominant driving force is wind
- **single-sided double-opening** where the driving force utilises a 'combined wind and stack' effect
- **cross-ventilation** which places extracts on the leeward face of a room
- **stack/atrium ventilation** where the main driving force is the convection of plumes of less dense warm air from sources of heat gains

Mechanical ventilation is elucidated upon in *Approved Document F* in facilitating three main methods;

- **extract ventilation** where, for example, pollutants may be extracted at source in a chemistry laboratory
- **purge ventilation** for rapid dilution of pollutants or water vapour within spaces
- **whole building ventilation** which provides continuous ventilation of spaces at a low rate while providing a fresh air supply to the building on top of localised extract ventilation for special zones

Similarly, *CIBSE AM13* outlines the three main types of mixed-modal ventilation as;

- **complementary mixed-mode** where mechanical systems work in conjunction with natural ventilation in the provision of either a greater ventilative volume of air or cooling beyond the means that can be provided by natural ventilation alone
- **contingency mixed-mode** where spaces in the building are allocated during the design stage for supply risers, ductwork, and mechanical plant which may be needed if natural ventilation strategies fail
- **zonal-mixed mode** where different areas of the building operate natural or mechanical ventilation depending on zonal requirements

The challenge of designing ventilation for schools are primarily attributable to high occupancy rates compared with other types of buildings with 'stuffy' classrooms having been an anecdotal complaint from many generations of schoolchildren, and the increasing use of information communication technology (ICT) equipment and the effect that this has on small power loads. Compounded with the predicted warming scenarios, providing health and thermal comfort through ventilation seems a daunting prospect.

Thermal analysis computer simulation

However, stakeholders and building designers are working in conjunction to meet the BSF brief in providing sustainable schools. A tool in the design process has been the computer simulation which has advanced to the extent that the effect of building apertures can be used to project the resultant temperatures indoors. Using such software has allowed the designers to continually review the design in an iterative process at each stage of the development. In addition, results of this have gone some way to inform the clients and interested stakeholders in the projected performance of the building and may allow clients to forecast their budgets pertaining to energy expenditure of the schools.

Research aims

The aim, therefore, of this study is to firstly construct thermal analysis models of three newly-constructed Central London schools under the *Building Schools for the Future* programme. This will be achieved through consultation with the architects of the schools, although where information influencing modelling is unavailable, referenced assumptions will be made.

The schools will then be simulated for their summertime thermal performance (as defined by *Building Bulleting 101* overheating criteria) under the present-day design summer year (DSY2004) weather file, and then for DSYs for the periods 2011-2040 (2020s), 2041-2070 (2050s), and 2071-2090 (2080s). The weather files for these periods will represent the forecast climatic conditions under the UKCIP02 'medium-high' warming scenario.

Thirdly, possible adaptation strategies for ventilation will be modelled and simulated to determine which best meets the BB101 overheating criteria under each time period of the warming scenario.

With the twin challenges of creating a new generation of educational facilities against the context of increased thermal discomfort and the need for a reduction in energy consumption, the design of suitably ventilated schools has never been more important.

CHAPTER TWO

Literature Review

2

An assessment of current literature pertaining to summer overheating in newly built schools is somewhat problematic because of a lack of existing studies in that particular area. Even harder to come by are intervention studies, theoretical or implemented, into assessing the possible remediation ventilation strategies that can be employed in certain types of climates.

Many studies exist however, regarding the control of carbon dioxide (CO_2) levels in schools, which has so far served as a marker as to the ventilation efficiency of classrooms and their ability to provide good indoor air quality. A study undertaken in 8 primary schools built after 1995 (*OPDM* 2006) indicated that in half of the samples, ventilation rates were less than 3l/s/p as stipulated by the School Premises Regulation (*E(SPR)*, 1999). Furthermore, only in 4 out of 10 cases was the mean CO_2 level less than the advised standard of 1000ppm. Extreme examples include daily average CO_2 levels of 1957ppm across seven classrooms in four schools (*Coley*, 2002) with corresponding low fresh air supplies of 1.38l/s/p against the implied level of 8l/s/p required to maintain an average CO_2 concentration of 1000ppm. Instantaneous CO_2 concentrations yield a much more striking picture with intermittent values as high as 5000ppm (*Brennan*, 1991). A comparison of CO_2 concentrations in British schools with that of continental European schools show similar levels with two Swedish schools reporting averages of 1420 and 1850ppm (*Norback*, 1995) and a classroom in a 1980s-built Danish school exceeding 2500ppm CO_2 for 73% of test occupied hours (*Potting*, 1987). Despite implicit low levels of ventilation (implicit, because of measurements through carbon dioxide concentration), Coley (2002) and Mumovic (2006) suggest that the potential to ventilate at 8l/s/p exists. Furthermore, the employment of purge ventilation was found to reduce the CO2 concentration by 1000ppm (*Griffiths and Eftekhari*, 2008); which need not be during the night, but a purge time of 10 minutes was demonstrated to have supplied approximately 200 l/s and reduced the CO_2 concentration accordingly.

Despite the 8l/s/p guideline ventilation rate, *Apte* (2000) and *Seppanen* (1999) suggest that rates below this do not necessarily suffice for the removal of pollutants from other sources. Furthermore, low ventilation rates in classrooms have been linked to health symptoms such as the exacerbation of allergen sensitivities in rooms with a high formaldehyde concentration (>0.05ppm) leading to chronic irritation and also were potential carcinogens (*Daisey et al.*, 2003). A large study of 1410 school staff in 38 Swedish schools by Smedje *et al.* (1996) determined that higher concentrations of moulds and microbial volatile organic compounds (VOCs) due to poor ventilation rates wee associated with asthma, even with the control of other variables. In addition, although ventilation rates may be designed to be higher under a natural ventilation strategy, Bassett and Gibson (1999) indicate that significant populations of bacterial and fungal species were present in naturally ventilated classrooms. Pollutant population is compounded by the fact that schools use an increasing amount of information communication technology (ICT)-related equipment, maximum ventilation rates will have to be devised accordingly in anticipation for the high heat gains of 125W for the average PC (*CIBSE Guide A*, 2005). Ventilation rates consistent with CO_2 levels above 1000ppm are indicative of ventilation rates that are unacceptable with respect to the sense of smell resulting from body odours (*Daisey et al.*, 2003). Inadequate ventilation will obviously result in higher internal temperatures, but also in the increase in VOCs such as phenol and formaldehyde causing a sensory pollution load of three times that of a person, per computer (*Bako-Biro et al.*, 2004). In addition, *Bako-Biro et al.*, determined an increase in the percentage of people dissatisfied (PPD) from 13 to 41% PPD when in a room using computers for a prolonged period of time (6 hours) at a ventilation rate of 10l/s/p.

However, the assessment of thermal comfort must also take into account of air movement where heat exchange can occur if there is a temperature differences across and air and skin and freshness (i.e. air change) is a key factor in its provision (*Clements-Croome*, 2008). McIntyre (1980) argues that air movement is detectable above 0.35m/s depending on metabolic rate and that discomfort is at a maximum if, at 0.3m/s, the frequency of air fluctuations is at 0.5Hz. Therefore, ventilation strategies must be designed to either capitalise upon air movement (where the ΔT and therefore cooling capacity is small) and trick the occupant into feeling cool, or to reduce air movement when draughts become noticeable.

The ventilation performance of schools and the corresponding effect on thermal conditions and indoor air quality on schoolwork performance were assessed by Mendell and Heath (2005). However, Wargocki and Wyon (2006) argue that behavioural implications cannot be extrapolated to children because of their vulnerability compared to adults, high occupant density within classes, the compulsory nature of school and limited control over their thermal comfort, with ventilation depending on teachers and uncomfortable uniforms.

While this study will not aim to predict the behaviour of schoolchildren under various degrees of thermal comfort, an area of exploration identified will be the efficacy of the provision of thermal comfort using various ventilation strategies, assessing where they are projected to fail in the future, and devising suitable remediation strategies for them. This will be achieved by a modelling methodology similar to that employed by Pegg *et al.* (2005) and will be assessed against the overheating guidelines laid out in *Building Bulleting 101: Ventilation Design for Schools*

There should be no more than 120 hours when the air temperature in the classroom rises above 28°C

Ther average internal to external temperature difference should not exceed 5°C (i.e. the internal air temperature should be no more than 5°C above the external air temperature on average)

The internal air temperature when the space is occupied should not exceed 32°C

CHAPTER THREE

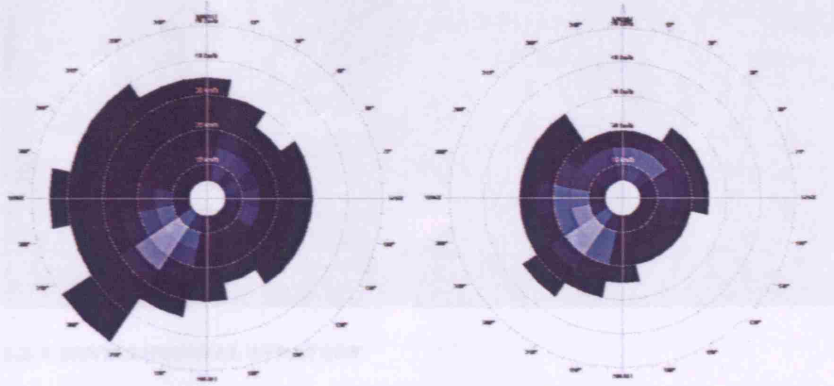
Methodology

3

3.1 Microclimate Overview

Given that the three schools assessed in this study are all relatively close to each other (to the extent that sampled weather data from one Central London source can be applied to each) and similar in urban context, it is worth outlining the overall climatic conditions extant on all sites.

The wind profile of all schools is described by southeasterly prevailing winds throughout the year, which maintains frequency but reduces in intensity during the summer months. Concurrently, greater frequencies of low-speed wind from other directions are seen, as illustrated in Figure 3-2. This implies that in the assessment of summertime thermal performance, wind-driven ventilation will have less of an effect than it would during other seasons.



Figures 3-1 and 3-2

Wind roses for Paddington Academy annually (Fig 1, left) and in summer (Fig 2, right). *Weather Tool, EcoTect*

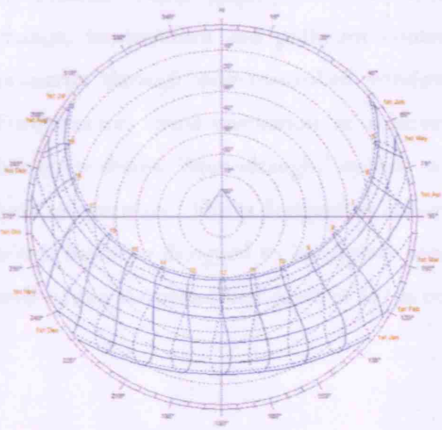


Figure 3-3

Sunpath diagram on Paddington Academy. *Solar Tool, EcoTect*

For all sites, the sun-path diagram indicates that all schools will experience a high Vertical Sun Angle on their southern facades. In addition, it can be seen that from

1st May to 1st October, the sun will occupy the southwest quadrant of the sky for more of the occupied hours than at any other orientation.

The designers of the three schools have thus used this information to inform the layout, character and operation of the buildings.

3.2 Haverstock School

Situated in the London Borough of Camden, Haverstock School is a 1,500-pupil education facility completed in 2005. The form of the building assumes 1- to 3-storey elements arranged around a single landscaped courtyard. The building also acts as a landmark in the borough, accentuated by a distinctive multicoloured southwest-facing façade along Haverstock Hill and Chalk Farm Road.

Figure 3-4

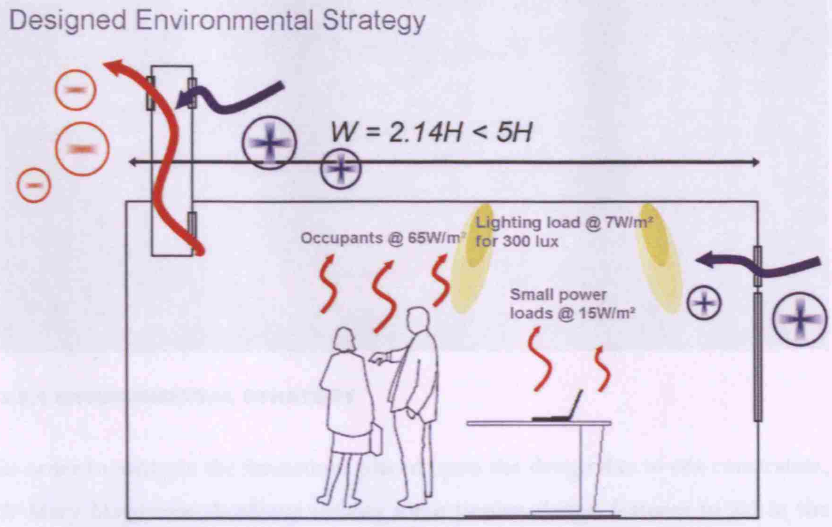
North-facing view of Haverstock School upon completion. Captured from *Windows Live Maps 2008*

3.2.1 ENVIRONMENTAL STRATEGY

Haverstock School employs natural ventilation as a means of facilitating air change, temperature and pollutant control across each of the 64 classrooms primarily through user-controlled windows providing single-sided ventilation. Furthermore, cross-ventilation is achieved by the utilisation of a split-duct buoyancy-driven 'Monodraught' system which is controlled by the room's dry bulb temperature. This is designed in consideration of the depth of the classroom, which has been designed to be slightly more than twice the height of the room; well within the prescribed depth of $5H$ as outlined in *CIBSE AM10* (2005).

Figure 3-5

Designed environmental strategy of a typical classroom at Haverstock School



As well as facilitating ventilative air movement across the classroom, thermal comfort is provided by the restricting of solar gains through the employment of fixed external louvers on south-facing facades.

An Information Communications Technology (ICT) suite is located on the ground floor on the southwest-facing façade of the northwest-oriented wing and is characterised by high internal heat gains from the use of upto 22 PCs and other equipment. The ventilation strategy employed in the ICT room is the same as that with other typical classrooms, albeit with a greater openable window area to increase the volumetric flow rate. In addition, higher ceilings than elsewhere in the building permits warm air to convect from head-level and so as to decrease thermal discomfort.

3.3 St Mary Magdalene Academy

St Mary Magdalene Academy is a newly-built (final phase completion 2008) education facility designed for 2- to 16-year olds. The building is composed of three distinct elements arranged and linked around external courtyards; a central 3-storey block for the secondary school, an appended southwest-oriented wing for children of nursery- and primary-school age, and a northeast-oriented three-storey multi-use gymnasium area (MUGA) connected to the central hub of the secondary school but a ground-floor spoke.

Figure 3-6

North-facing view of St Mary Magdalene Academy under construction, probably taken around 2006. Captured from *Windows Live Maps 2008*

3.3.1 ENVIRONMENTAL STRATEGY

In order to mitigate the limitations placed upon the design due to site constraints, St Mary Magdalene Academy utilises some passive design features to aid in the provision of thermal comfort:

- Self-shading over certain areas of the building due to multiple levels and architectural design features
- Appropriate specification (in accordance with *Approved Document L2A*) and distribution of glazing across facades; a maximum of 40% glazing on north-facing facades to maximise diffuse solar insolation, 32% glazing on south-facing facades, and a maximum of 12% glazing on horizontal facades, such as rooflights, to admit natural daylighting (maximum 10% daylight factor in the atrium, 2% in classrooms) but limit direct short-wave infra-red solar gains
- Employment of brise soleil to limit high-angle solar penetration
- Facilitation of night-cooling with louvred narrow windows, meeting site security guidelines during unoccupied hours
- Exposed thermal mass in soffit ceilings to store and radiate coolth during night-cooling
- Actuator vents in rooflights in deep-plan rooms which do not lend itself to single-sided ventilation

In addition, it is worth briefly highlighting the strategies undertaken by the designers of St Mary Magdalene Academy to embody sustainability and reduce carbon emissions:

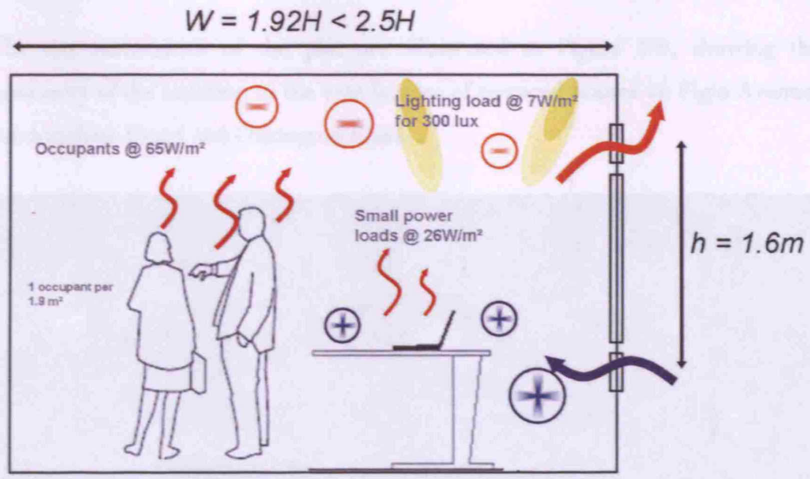
- On-site renewable electricity generation by woodchip-fed biomass boiler
- Use of high efficiency condensing boilers
- Heat recovery in ventilation system

- Variable speed fans
- Earth tubes fed to atrium to provide some limited ground coupling
- Integrated Building Management System (BMS) with localised manual override for efficient climate control of all areas

Figure 3-7

Designed environmental strategy for a typical classroom at St Mary Magdalene Academy

Designed Environmental Strategy



The Academy's design features a holistic approach to ventilation, adopting a zonal/contingency mixed-mode strategy with naturally ventilated areas wherever possible. The arrangement of the classrooms in the central hub of the building are such that good daylight penetration is achieved and single-sided double-opening natural ventilation administered, while a full-height atrium is featured for use as a multipurpose area. In addition, a potential for night-purge ventilation has been employed through separate apertures in each classroom.

Smaller internal rooms immediately facing the atrium and not exposed to the external environment are mechanically ventilated by a low-velocity displacement-type system with heat rejection plantwork sized upon an assumed external dry-bulb temperature of 30°C. Furthermore, comfort cooling can be administered by use of an air cooled chiller supplied to the internal rooms when fully occupied. Comfort cooling has allowed the mechanical ventilation plant to be smaller, which has reduced any adverse effects on space and acoustics arising from mechanical ventilation systems.

3.4 Paddington Academy

Paddington Academy is a newly-built 1175 pupil education facility designed for 11- to 18-year olds. Situated in a densely-populated residential area between Maida Vale and Westbourne Park, the Academy is a significant 9,884m^2 landmark in the local area.

The size restrictions of the plot are illustrated in Figure 3-8, showing the proximity of the building to the rear facades of terraced houses on Elgin Avenue, Sandringham Court and Oakington Road.

Figure 3-8

Northeast-facing view of site of Paddington Academy under construction. Captured from *Windows Live Maps 2008*

3.4.1 SITE-SPECIFIC MICROCLIMATE ANALYSIS

The local area around Paddington Academy is characterised by high external noise levels of 57dB(A) and itself has been designed to meet the acoustic requirements of DfES Building Bulletin 93. In addition, the concentration of NO_2 species in the vicinity of Paddington Academy is estimated to be approximately 33µg/m^3 (*London Air*, 2008) compared with an area-weighted guideline maximum value of 40µg/m^3 prescribed by Westminster Borough Council.

As a result of spatial constraints and the planning considerations related to the overlooking dwellings, the overall form of Paddington Academy has been designed with minimum sprawl and the new building itself assumes a compact form. The implications of this on efficient passive design is the deep-plan (>15m depth) nature of the building and the resulting limitations placed on provision for natural ventilation as described in *CIBSE AM10* (2005). Furthermore, the compact form of the building does not lend itself to self-shading, reducing the ability to limit solar exposure.

3.4.2 ENVIRONMENTAL STRATEGY

In order to mitigate the limitations placed upon the design due to site constraints, Paddington Academy utilises some passive design features to aid in the provision of thermal comfort:

- Although scope for self-shading is limited given the form of the building, apertures are recessed within the façade to provide shading from high-angle sunshine
- Translucent vertical fins prevent direct low-angle solar penetration, yet permits diffuse natural lighting
- Large areas of glazing, such as those enclosing atria and circulation spaces, are designed as high performance low-emissivity glass to reduce short-wave infra-red solar penetration
- Facilitation of night-cooling with narrow windows, meeting site security guidelines during unoccupied hours
- Exposed thermal mass in soffit ceilings to store and radiate coolth during night ventilation
- Ground-coupled heat source (winter)/sink (summer) through use of a 1m-deep sub-surface undercroft

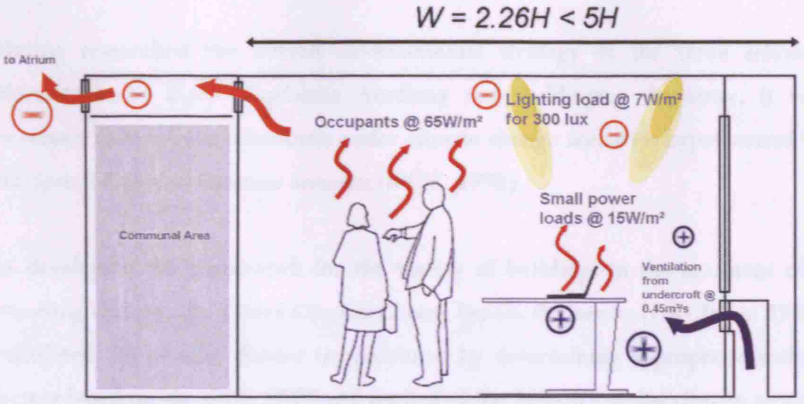
Complementary with these passive design features, Paddington Academy uses a low-pressure mechanical ventilation system for pollutant and heat gain expulsion from classrooms. This was selected, in part, due to energy efficiency considerations as well as the acoustic requirements for the site. Furthermore, the ventilation strategy of the Academy is designed with the "*build tight, ventilate right*" ethos in mind, and as such, fabric permeability is limited to $10m^3/hm^2$ at a maintained pressure of 50Pa.

Mechanical ventilation of the Academy is provided for by a basement-level undercroft that is pressurised by low speed fans. Air is supplied to classrooms at window sill-level grilles via insulated ducts concealed within the cladding. Exhaust air is then designed to exit the classrooms via attenuators into the nearest circulation areas, transferring via corridors. Background infiltration is provided at 8 l/s/p through trickle vents that can be 'throttled down' to avoid cold draughts.

Figure 3-9

Designed summer environmental strategy for typical east- and west-facing classrooms

Designed Environmental Strategy



The ventilation rate into the classrooms is controlled by motorised dampers that modulate the fan speeds depending on local occupancy and temperature demands. The Stage D Report for Paddington Academy anticipates that cooling will be needed as the ventilation provided by the ground-coupled undercroft will be inadequate to expel the forecast internal heat gains and provide thermal comfort during summer. This is reinforced by Section 4.1.3 *Building Bulletin 101* (2006) which suggests that higher ventilation rates or comfort cooling will be needed in most circumstances.

3.5 Thermal Simulation Modelling Methodology

3.5.1 CLIMATE CHANGE WEATHER FILES

Having researched the overall environmental strategy of the three schools, Haverstock, St Mary Magdalene Academy and Paddington Academy, it was necessary to test their robustness under climate change scenarios hypothesised by the *Special Report on Emissions Scenarios* (IPCC, 1998).

In developing the framework for the testing of buildings in the scenarios of a warming climate, the *United Kingdom Climate Impacts Programme* (UKCIP) in 1998, calculated the possible future temperatures by determining appropriate scaling factors based on the IPCC SRES and applied to the *HadCM3* global climate model. The scaling factors of temperatures are shown in Figure 3-10.

Figure 3-10

Climate scaling factors produced by UKCIP02 for various emissions scenarios

Average global temp. change relative to 1960-1990	Climate scaling factor (CSF)	Emissions scenario	Timeslice
0.79	0.24	Low	2020s
0.88	0.27	Medium-Low	2020s
0.88	**0.27**	**Medium-High**	**2020s**
0.94	0.29	High	2020s
1.40	0.43	Low	2050s
1.60	0.50	Medium-Low	2050s
1.90	**0.57**	**Medium-High**	**2050s**
2.00	0.61	Low	2080s
2.20	0.68	High	2050s
2.30	0.71	Medium-Low	2080s
3.30	**1.00**	**Medium-High**	**2080s**
3.90	1.18	High	2080s

It should be noted that the 2020, 2050, and 2080s timeslices refer to the periods 2011-2040, 2041-2070, and 2071-2090 respectively.

It was decided to assess the three schools in the 'Medium-High' A2 emissions scenario, given the perceived market-driven approach to climate change adaptability in the UK and that the likelihood of each of the scenarios were equally probable. In addition, the proportional increase in temperatures attributed to this scenario offered a robust testing of the summer performance of the three schools, given the resulting climate scaling factors. The corresponding weather files for use in TAS for the Medium-High scenarios in London were obtained from *Haw* (2002).

3.5.2 DEFINITION OF SUMMERTIME TEST PERIOD

In testing the rigour of the designed ventilation strategies for each of the three schools under 'Medium-High' warming scenarios for the 2020s, 2050s and 2080s, it was necessary to define the test periods within those timeslices for which summertime thermal performance would be recorded. Building Bulletin 101 specifies its summertime overheating criteria as,

"the occupied period of 0900 to 1530, Monday to Friday, from 1st May to 30th September"

In testing within this period, the calendar settings in the simulation were configured so that 1st January fell on a Monday. The occupied period in the range prescribed by Building Bulletin 101 required that a 6-week summer holiday, taken from Thursday 19th July to Tuesday 4th September, was omitted from analysis.

3.5.3 MODELLING AND ZONING STRATEGY

Assessment of summer thermal performance of the three schools was achieved by constructing simplified thermal models of the buildings in *Thermal Analysis Software* (TAS). The software is used as a tool during an iterative design process to inform architects, engineers and consultants of the thermal performance of buildings, taking into account of the building envelope, aperture specification, internal heat gains, and inter-zonal air movement. In assessing summertime thermal performance, test zones were identified.

The test zones illustrated in Figure 3-11 represent identical classrooms that were amalgamated into one thermal zone for analysis, although physical partitions true to the layout were modelled in TAS. The drawing of the models involved the following main assumptions to promote simplicity:

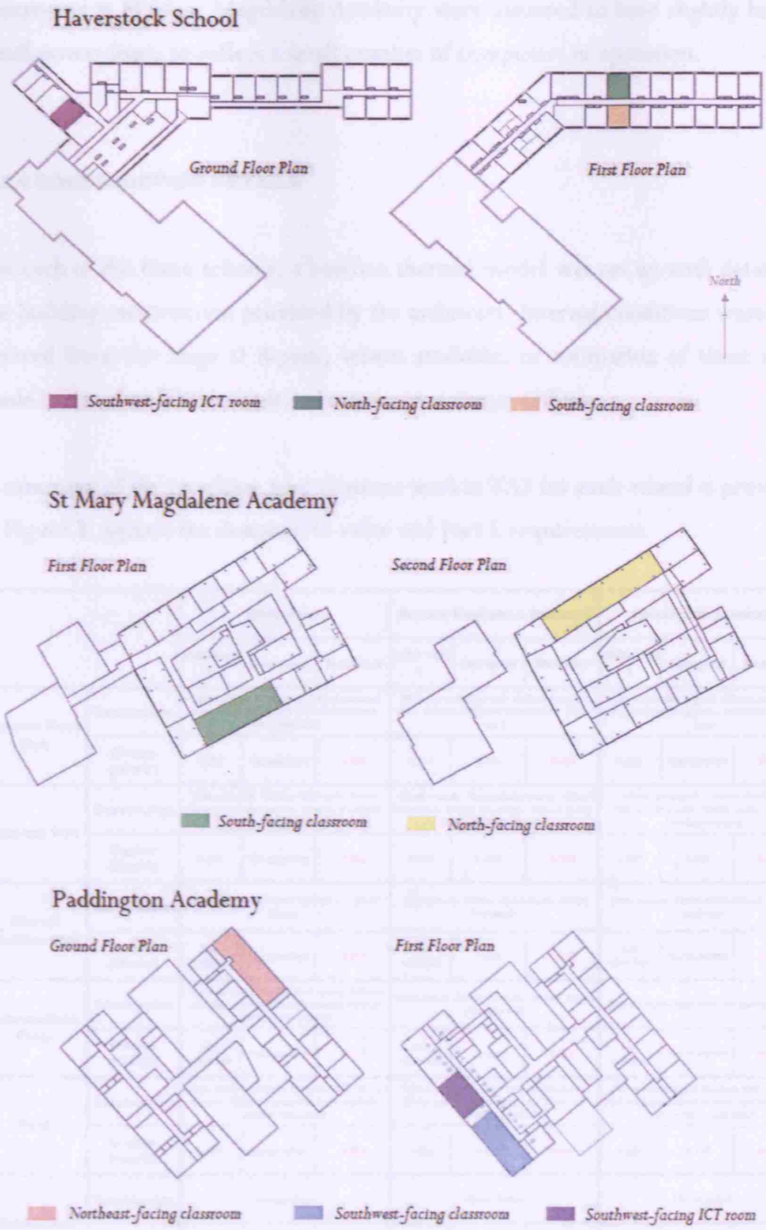
- Grouping of several identical areas into a single thermal zone that had similar internal conditions, specifically gains profile and inter-zonal air movement

- Exclusion of certain areas of the building from the model if partitions between the test area and the excluded area were assumed to be adiabatic (for example, the simplification of the west wing of St Mary Magdalene Academy)
- Thermal zones were not created vertically as it was assumed that the ceiling heights would not be high enough to facilitate significant temperature stratification

It was decided that the best evaluation of summertime overheating would be achieved by modelling areas which performed the same function, and were subject to similar environmental conditions, in the three schools. As a result, south-facing classrooms were chosen in each of the schools, as well as either one or two classrooms at other orientations for comparison. In addition, where possible, classrooms that taught year 9 were chosen so as to standardise the occupant heat gains among 12- to 13-year olds. In practice, this was difficult to achieve as the classrooms were occupied by all years of the school.

Figure 3-11

Location of thermal zones tested for summer overheating in each school



In Haverstock School and Paddington Academy, dedicated ICT suites were also selected for analysis given the anticipated high internal heat gains from the operation of computers, whiteboards and printers. At St Mary Magdalene Academy, the attitude of the school towards ICT was that it should be a tool integrated with learning, and not a distinct part of the curriculum, thereby foregoing the necessity to have a dedicated ICT suite. As a consequence, classrooms at St Mary Magdalene Academy were assumed to have slightly higher small-power loads to reflect a small number of computers in operation.

3.5.4 CONSTRUCTION DETAILS

For each of the three schools, a baseline thermal model was set up with details of the building construction provided by the architects. Internal conditions were also derived from the *Stage D Reports*, where available, or estimation of these were made in line with *CIBSE Guide A: Environmental Design* (2006).

A summary of the envelope specifications used in TAS for each school is provided in Figure 8, against the designed U-value and Part L requirements.

Figure 3-12

Construction details for main building elements for all three schools, compared with designed target U-values and area-weighted U-values as prescribed by CIBSE Guide A: *Environmental Design* (2006)

		Haverstock			St Mary Magdalene Academy			Paddington Academy		
		2006 Part L	Designed	Modelled	2006 Part L	Designed	Modelled	2006 Part L	Designed	Modelled
Ground Floor Slab	Construction	10mm carpet, 5mm steel, 50mm concrete screed, 200mm cavity, 200mm concrete, 50mm insulation			20mm concrete screed, 120mm concrete slab, 100mm polystyrene insulation, 30mm sand			30mm concrete screed, 300mm concrete slab, 150mm polystyrene insulation, 50mm sand		
	U-value (W/m^2K)	0.250	Not specified	0.232	0.250	0.250	0.266	0.250	Not specified	0.177
External Wall	Construction	12mm plaster, 102mm brickwork, 50mm insulation, 50mm cavity, 102mm brickwork, 19mm plaster			12mm plaster, 15mm plasterboard, 150mm blockwork, 80mm insulation, 100mm cavity, 24mm Corium cladding			140mm blockwork, 200mm insulation, 100mm blockwork, 50mm cavity, 25mm Cumaru cladding		
	U-value (W/m^2K)	0.350	Not specified	0.294	0.350	0.350	0.378	0.350	0.258	0.258
Internal Partition Wall	Construction	10mm plaster, 100mm brickwork, 10mm plaster			4mm plaster, 12mm plasterboard, 80mm brickwork			8mm plaster, 12mm plasterboard, 80mm brickwork		
	U-value (W/m^2K)	Not specified	Not specified	1.341	Not specified	1.800	1.815	Not specified	Not specified	1.900
Intermediate Floor	Construction	15mm acoustic tile, 200mm cavity, 200mm concrete, 50mm concrete screed, 200mm cavity, 10mm carpet			6mm carpet, 20mm concrete screed, 80mm concrete slab			300mm lightweight exposed concrete slab		
	U-value (W/m^2K)	Not specified	Not specified	0.764	Not specified	3.300	3.218	Not specified	Not specified	0.285
Roof	Construction	10mm plaster, 150mm concrete slab, 50mm screed, 100mm insulation, 2mm asphalt, 200mm aggregate			120mm concrete slab, 140mm insulation, 50mm cavity, 50mm concrete, 3mm felt, 12mm aggregate			350mm lightweight concrete slab, 80mm slab insulation, 8mm bitumen asphalt layer, 40mm stone aggregate		
	U-value (W/m^2K)	0.250	Not specified	0.215	0.250	0.250	0.257	0.250	0.196	0.196
Internal Door	Construction	Not specified			45mm timber			45mm timber		
	U-value (W/m^2K)	2.200	Not specified	Not specified	2.200	2.000	1.340	2.200	Not specified	1.340
Glazing	Construction	6mm kappafloat, 12mm air cavity, 6mm clear with sputtered low-E coating			6mm clear toughened, 12mm air cavity, 6mm clear with sputtered low-E coating			6mm clear toughened, 16mm air cavity, 8.76mm clear with sputtered low-E coating		
	U-value (W/m^2K)	2.200	Not specified	1.808	2.200	2.000	1.936	2.200	1.400	1.262
Aperture Frame	Construction	15mm aluminium			50mm timber			50mm timber		
	U-value (W/m^2K)	2.200	Not specified	5.880	2.200	2.000	1.933	2.200	Not specified	1.933

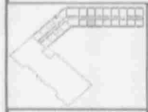
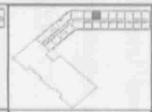
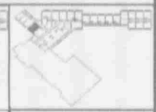
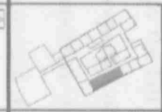
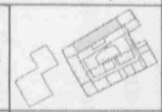
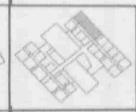
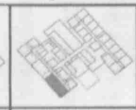
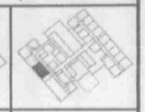
Assumptions made in the allocation of construction details for major elements included the simplification of the envelope; each of the schools had certain architectural gestures made along each façade of the school. Simplification of this involved assessing the type of façade most relevant to the thermal performance of the test zones. In addition, the U-value of the different facades were approximately consistent with 2006 Part L area-weighted guidelines. It was then considered that in light of this, minor differences in other thermal properties of the cladding material (for example, thermal conductivity of corium brick slips and Cumaru panels) could be negated.

3.5.5 SCHEDULING OF INTERNAL GAINS

Schools are characterised by high occupancy rates of 1.5-2.4m^2 per person compared to offices at 10m^2 per person (*CIBSE Guide A*, 2006).

Figure 3-13

Internal heat gains that were used in the configuration of the three school models

		Haverstock School			St Mary Magdalene Academy		Paddington Academy		
									
		South-facing classroom	North-facing classroom	Southwest-facing ICT room	South-facing classroom	North-facing classroom	Northeast-facing classroom	Southwest-facing classroom	Southwest-facing ICT room
Boundary Conditions	Occupants	25	25	25	30	30	30	30	30
	Thermal Zone Area (m²)	33.4	40.5	41.5	163.0	286.8	227.7	189.8	120.5
	Classroom Area (m²)	33.4	40.5	41.5	54.3	57.4	56.9	63.3	60.3
	Classroom Volume (m³)	85.1	103.3	143.2	214.6	220.2	204.9	227.7	217.0
Internal Gains (W/m²)	Occupant Sensible (W/m²)	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0
	Occupant Latent (W/m²)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
	Lighting (W/m²)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
	Equipment (W/m²)	15.0	15.0	60.2	26.5	25.9	15.0	15.0	75.2
Total Gain	Gain Density (W/m²)	87.0	87.0	132.2	98.5	97.9	87.0	87.0	147.2
	Total Gain (W)	2904.4	3525.8	5487.4	5351.2	5615.7	4952.5	5502.8	8872.1

The assumptions that have been made in configuring the internal conditions of each of the assessed zones are outlined below:

- Occupant thermal output assumed to be 70% of an adult, 53W/m^2 sensible and 40W/m^2 latent (*CIBSE Guide A*, 2006), consistent with the proportional body surface areas of 12- to 13-year olds of 1.33m^2 compared to 1.75m^2 for an adult (*BNF*, 2008)
- Applied lighting load of 7W/m^2 consistent with fluorescent triphosphor lamps providing 300 lux illuminance to a 0.8m-high working plane (*Table 6.4, CIBSE Guide A and CIBSE Code for Lighting* 2002)
- All gains are applied from the hours of 0900 to 1530 during occupied days
- Classrooms in St Mary Magdalene Academy are assumed to have slightly higher equipment gains given the school ethos to integrated ICT learning and are calculated based on 15W/m^2 small power loads plus 5 average PCs (55W) and 5 17" monitors (70W)
- ICT suites in Haverstock School and Paddington Academy based on 20 and 30 average PCs with 17" monitors respectively
- St Mary Magdalene Academy S-facing thermal zone has 3 classrooms, N-facing thermal zone 5 classrooms, Paddington Academy NE-facing thermal zone has 4 classrooms, SW-facing thermal zone 3 classrooms, and the SW-facing thermal zone has 2 ICT room

3.5.6 APERTURES AND ADAPTIVE VENTILATION STRATEGIES

For Haverstock School and St Mary Magdalene Academy, natural ventilation is the main ventilation method for the teaching spaces, while Paddington Academy relies on a low-pressure mechanically ventilated system. As a result, the configuration of the apertures in Haverstock and St Mary Magdalene Academy are especially important in determining the penetration depth, and cooling capacity of the introduced air and whether it is facilitated by the stack effect, or wind forcing. Each of the three schools were modelled with their designed ventilation strategy as well as adaptation strategies that could be applied to mitigate any potential summertime overheating. A summary of the different aperture types and ventilation strategies are presented in Figures 3-14, 3-15 and 3-16.

In the last column of each table, an estimate of the theoretical maximum cooling capacity of each ventilation strategy is made. This takes into account only the aperture types and not the effect of night-ventilation which, due to the time constant τ of heat storage and release in thermal mass, makes it complicated to evaluate a static picture. Furthermore, these are indicative only because the algorithms used to calculate them have been simplified to an extent as they do not account for variability of wind velocity, turbulence in the air stream, or the Coandă effect. Instead, the estimated cooling capacities under each of the ventilation strategies are functions of internal-external temperature difference (calculated for $\Delta T=5°C$, in line with Building Bulletin 101), wind velocity, and aperture area. Nevertheless, these calculations are presented to demonstrate the intended efficacy of the adaptation strategies.

The NORMA method calculations (*Santamouris*, 1996) used in the determination of the cooling capacity involved the analysis of the volumetric flow rate of air in it's constituent horizontal and vertical components,

Equation 3-1

Volume flow rate of air due to wind-driven ventilation

$$Q_w = \frac{1620}{3600} B^{-1.02} V \sqrt{\Delta C_P} \text{ given } B = \frac{1}{\sqrt{A_1^2 + A_2^2}}$$

Where Q_w = volumetric flow rate due to wind-forcing in m^3/s, V = wind velocity in m/s, $A_{1,2}$ = area of windward openings in m^2, and ΔC_P = 0.51 the difference in pressure coefficients between windward and leeward apertures for a terrain roughness of zh = 0.40 corresponding to suburban terrain (Santamouris, 1996)

Equation 3-2

Volume flow rate of air due to stack driven ventilation

$$Q_s = C_d A \left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\varepsilon^2)^{1/2}} \right] \left(\frac{\Delta T g H_1}{\overline{T}} \right)^{1/2} \text{ given } \varepsilon = \frac{A_1}{A_2} \text{ and } A = A_1 + A_2$$

Where Q_s = volumetric flow rate due to stack effect in m^3/s, C_d = 0.6 discharge coefficient as outlined in CIBSE AM10 (2005), $A_{1.2}$ = area of windward openings in m^2, ΔT = average temperature difference between inside and outside, $\overline{T}$ = average of inside and outside temperatures in °C, g = $9.81 m/s^2$ gravitational acceleration, and H_1 = height between the upper and lower leeward windows in m

The combination of the horizontal (wind) and vertical (stack) components in providing ventilation, at a total volumetric flow rate V_T (in m^3/s) is then expressed by,

Equation 3-3

Combined wind and stack effect

$$V_T = \sqrt{Q_w^2 + Q_s^2}$$

From this, the cooling capacity of the ventilated air, whether naturally or mechanically introduced, can be deduced in the usual way,

Equation 3-4

Cooling capacity of either wind- or stack-driven ventilation, or combined wind and stack effect

$$q = \rho V_T c \Delta T$$

Where q = cooling capacity in W/m^2, ρ = $1.20 kg/m^3$ density of air at T=20°C and 101.36kPa, and C = 1.02kJ/kgK specific heat capacity of air

Equations 3-1 to 3-4 were applied to the boundary conditions and calculated in an Excel spreadsheet to give the values quoted in the last columns of Figures 3-14, 3-15 and 3-16. Estimating the potential cooling capacity under each of the different ventilation strategies allowed the assessment of each to be made quantitatively. In addition, the characteristics of natural ventilation could be assessed using Equations 3-2 and 3-4 under increased outdoor temperatures, whereby the contribution of the stack effect, Q_s, as a proportion of the total natural ventilation, V_T, may be expected to increase.

Figures 3-14, 3-15 and 3-16 show the installed and adaptive ventilation strategies for each of the three schools.

Figure 3-14

Existing and adaptive aperture and ventilation strategies for Haverstock School

Haverstock School

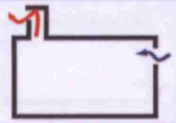
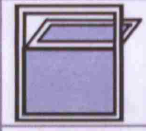
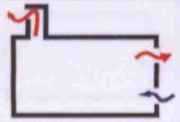
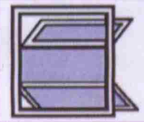
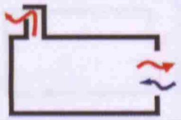
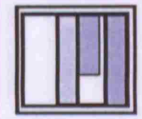
	STRATEGY	HYPOTHESISED STRATEGY	WINDOW TYPE	MAXIMUM OPENABLE WINDOW AREA	OPERATING SCHEDULE AND CONTROL MECHANISM	THEORETICAL MAXIMUM COOLING CAPACITY
a	Designed ventilation strategy: Upper bottom-hung manually-controlled window opened during occupied hours with high-level outlet through windcatcher. Night-ventilation through windcatcher			2.47 m²	Opened from 0900 to 1600. Windcatcher (2.56m² free area) open from 2300 to 0700 for night-ventilation	10.36 W/m²
b	Temperature-controlled double-opening single-sided ventilation with high-level outlet through windcatcher. Night-ventilation through windcatcher, upper and lower parts of window			4.07 m²	Starts opening at 20ºC, fully open at 25ºC. Windcatcher, upper and lower windows (5.86m² free area) open from 2300 to 0700 for night-ventilation	21.22 W/m²
c	Vertical louvred windows: Temperature-dependent, automatically-opening vertical sliding sash window with high-level outlet through windcatcher. Night-ventilation through windcatcher and sliding sash windows			7.17 m²	Starts opening at 18ºC, fully open at 28ºC. Windcatcher and window (9.73m² free area) open from 2300 to 0700 for night-ventilation	42.27 W/m²

Figure 3-15

Existing and adaptive aperture and ventilation strategies for St Mary Magdalene Academy

St Mary Magdalene Academy

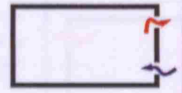
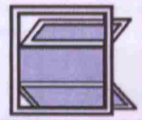
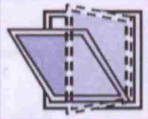
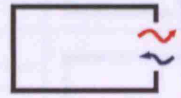
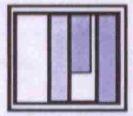
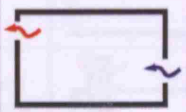
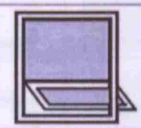
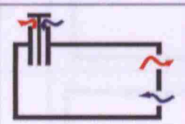
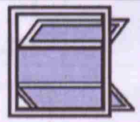
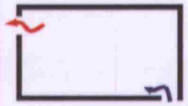
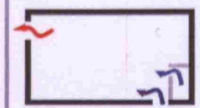
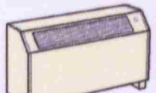
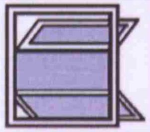
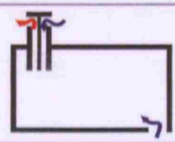
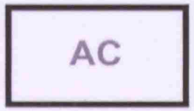
	STRATEGY	HYPOTHESISED STRATEGY	WINDOW TYPE	MAXIMUM OPENABLE WINDOW AREA	OPERATING SCHEDULE AND CONTROL MECHANISM	THEORETICAL MAXIMUM COOLING CAPACITY
a	Designed ventilation strategy: Double-opening single-sided ventilation opened during occupied hours. Night-ventilation through louvred windows			3.84 m²	Opened from 0900 to 1600. Separate apertures (1.44m² free area) open from 2300 to 0700 for night-ventilation	25.05 W/m²
b	Side-hung, temperature-dependent, automatically-controlled window. Night-ventilation through louvred windows			5.76 m²	Starts opening at 20ºC, fully open at 25ºC. Separate apertures (1.44m² free area) open from 2300 to 0700 for night-ventilation	33.56 W/m²
c	Vertical louvred windows: Temperature-dependent, automatically-opening vertical sliding sash window. Night-ventilation through louvred windows			7.56 m²	Starts opening at 18ºC, fully open at 28ºC. Separate apertures (1.44m² free area) open from 2300 to 0700 for night-ventilation	44.29 W/m²
d	Cross ventilation: Lower top-hung temperature-dependent automatically-controlled window with high-level outlets placed at rear of room. Night-ventilation through louvred windows			1.92 m²	Lower bottom-hung window starts opening at 20ºC, fully open at 25ºC. High-level vent always open. Separate apertures (1.44m² free area) open from 2300 to 0700 for night-ventilation	19.65 W/m²
e	Temperature-controlled double-opening single-sided ventilation. Split-duct type system at rear of room to facilitate cross ventilation and fresh air penetration. Night-ventilation through louvred windows			4.32 m²	Starts opening at 20ºC, fully open at 25ºC. Split-duct intakes and extracts always open. Separate apertures (1.44m² free area) open from 2300 to 0700 for night-ventilation	29.88 W/m²

Figure 3-16

Existing and adaptive aperture and ventilation strategies for Paddington Academy

Paddington Academy

	STRATEGY	HYPOTHESISED STRATEGY	APERTURE TYPE	OPERATING SCHEDULE AND CONTROL MECHANISM	THEORETICAL MAXIMUM COOLING CAPACITY
a	Designed ventilation strategy: Low-pressure inlet air supplied by ground-coupled undercroft. High-level outlets to circulation areas			Undercroft fan in operation from 0900 to 1600	118.49 W/m² Based on 0.45m³/s with supply T = ground T
b	Comfort cooling: Low-pressure inlet air supplied by ground-coupled undercroft, with peak-lopping by fan-coil units. High-level outlets to circulation areas			Fan coil unit starts operating when zonal dry bulb temperature reaches 28ºC, with maximum output at 32ºC	124.24 W/m² Based on 17,600Btu/h McQuay S06
c	Lower mean radiant temperatures: Low-pressure inlet air supplied by ground-coupled undercroft. High-level outlets to circulation areas. Night-purge ventilation through upper and lower parts of window			Open from 2300 to 0700 for night-ventilation	Not calculated
d	Low-pressure inlet air supplied by ground-coupled undercroft. Split-duct type system at rear of room to facilitate passive cross ventilation and fresh air penetration			Undercroft fan in operation throughout occupied hours. Split-duct (0.46m² free area) open from 0900 to 1600	145.70 W/m²
e	All air-cooling air conditioning, ~12,000Btu			Thermostat set to maintain zonal dry bulb temperature between 19ºC and 24ºC	102.35 W/m² Based on 15,000Btu/h Unionaire

CHAPTER FOUR
Results and Analysis

4

4.1 Data Analysis Methodology

Having input the parameters of each model, simulations were run using the London Design Summer Year weather file which sampled data from 1983 to 2004 and fitted an exceptionally hot summer from 1989. These simulations provided a benchmark to describe the current summertime performance of the three schools. Repeat simulations were then run for the 2020s, 2050s and 2080s periods under each of the different ventilation strategies. Thus a total of 52 datasets were obtained for the different permutations simulated, corresponding to 13 different ventilation strategies for 4 different time periods under the UKCIP02 'medium-high' scenario, across 3 different schools.

The data was retrieved from TAS .tsd files and imported into an MS Excel spreadsheet. A time series corresponding to hours, days and months, was fitted to the hourly data. In addition, the hourly data was identified by a day-marker in a separate column; 'W' for weekday, 'S' for Saturday/Sunday. Finally, a third column was added to the data to indicate occupied hours; '0' unoccupied hour and '1' occupied hour. This allowed the data to be automatically filtered in Excel to present all data from 9am to 4pm, Monday to Friday, from 1st May to 30th September, excluding the period 19th July to 4th September.

Formulae were then applied to the data to calculate overheating as a function of three parameters:

- Number of hours $19°C \leq T_{int} \leq 24°C$ (defined as thermally comfortable) using the `=COUNTIF(range,">=19")-COUNTIF(range,">=24")` algorithm
- Number of hours $T_{int} \geq 28°C$ using the `=COUNTIF(range,">=28")` algorithm
- Number of hours $T_{max} \geq 32°C$ using the `=COUNTIF(range,">=32")` algorithm
- Number of hours $\Delta T \geq 5°C$ using the `=COUNTIF(range,">=5")` algorithm

Histograms were then plotted for the data relevant to the overheating criteria and line plots were made of the internal temperature profile during the occupied hours.

In addition, the maximum, minimum, mean and standard deviations of all zonal temperatures were tabulated for each simulation to reinforce the characterisation of summertime thermal performance by the Building Bulletin 101 criteria. The warmest week was taken to be 13-20 June with the hottest day falling on 20 June, based on external weather data.

For the assessment of the mechanically-ventilated school, Paddington Academy, it was decided that since the designed ventilation strategy would perform better than natural ventilation, any adaptive changes, other than night-cooling and supplementary natural ventilation, would have to be mechanical in nature. Since mechanical ventilation can often control indoor climate more closely than natural ventilation and that an adaptation strategy may involve the conditioning of air, it was therefore concluded that an temperature-profile assessment of overheating under mechanically ventilated strategies would be misleading. Therefore, for Paddington Academy, the seasonal cooling loads necessary to maintain thermal comfort under each strategy are also calculated and presented.

4.2 Haverstock School

Presented in Table 4-1 are the results of TAS simulation for Haverstock School.

Table 4-1

Summary of simulation data for 3 zones of classrooms at Haverstock School under operation of designed and adaptive ventilation strategies for 2004, the 2020s, 2050s and 2080s

		Ground Floor Southwest-facing ICT Room				Ground Floor South-facing Classroom				Ground Floor North-facing Classroom			
		2004	2020s	2050s	2080s	2004	2020s	2050s	2080s	2004	2020s	2050s	2080s
Strategy A	Mean DBT (ºC)	29.0	30.1	31.4	33.2	30.7	31.9	33.3	35.2	30.9	32.1	33.4	35.3
	Standard Deviation (ºC)	4.0	4.1	4.1	4.2	3.3	3.4	3.5	3.6	3.2	3.3	3.4	3.5
	Maximum Temperature (ºC)	38.6	39.9	41.4	43.5	37.1	38.3	39.7	41.6	37.3	38.5	39.8	41.7
	Temperature Range (ºC)	19.5	19.9	20.4	21.2	18.1	18.4	18.8	19.3	17.8	18.1	18.5	19.0
	No. hours $20 \leq DBT(^{\circ}C) \leq 25$	110	28	25	210	86	28	27	72	88	28	27	53
	No. hours $\Delta T(^{\circ}C) \geq 5$	**493**	**496**	**493**	**494**	**491**	**492**	**496**	**496**	**496**	**496**	**495**	**495**
	No. hours $T(^{\circ}C) \geq 28$	**315**	**452**	**403**	**458**	**415**	**452**	**489**	**502**	**425**	**467**	**491**	**502**
	No. hours $T(^{\circ}C) \geq 32$	**124**	**271**	**234**	**324**	**202**	**271**	**338**	**417**	**214**	**291**	**349**	**423**
Strategy B	Mean DBT (ºC)	29.0	28.3	29.6	31.4	30.7	31.9	33.3	35.2	32.0	33.2	34.5	36.4
	Standard Deviation (ºC)	4.0	4.0	4.1	4.2	3.3	3.4	3.5	3.6	3.2	3.3	3.4	3.5
	Maximum Temperature (ºC)	38.6	37.9	39.4	41.5	37.1	38.3	39.7	41.6	38.5	39.7	41.0	42.9
	Temperature Range (ºC)	19.5	18.6	19.2	19.9	18.1	18.4	18.8	19.3	18.1	18.4	18.7	19.2
	No. hours $20 \leq DBT(^{\circ}C) \leq 25$	110	28	25	210	86	28	27	144	88	28	27	108
	No. hours $\Delta T(^{\circ}C) \geq 5$	**493**	**470**	**472**	**473**	**491**	**492**	**496**	**496**	**496**	**496**	**495**	**495**
	No. hours $T(^{\circ}C) \geq 28$	**315**	**273**	**338**	**398**	**415**	**453**	**489**	**502**	**425**	**467**	**491**	**502**
	No. hours $T(^{\circ}C) \geq 32$	**124**	**111**	**155**	**237**	**202**	**272**	**338**	**418**	**214**	**292**	**349**	**423**
Strategy C	Mean DBT (ºC)	27.4	28.4	29.5	31.2	30.7	31.9	33.3	35.2	30.9	32.1	33.4	35.3
	Standard Deviation (ºC)	3.5	3.6	3.8	4.0	3.3	3.4	3.5	3.6	3.2	3.3	3.4	3.5
	Maximum Temperature (ºC)	36.2	37.5	38.9	41.0	37.1	38.3	39.7	41.6	37.3	38.5	39.8	41.7
	Temperature Range (ºC)	17.2	17.7	18.3	19.2	18.0	18.4	18.8	19.3	17.8	18.1	18.5	19.0
	No. hours $20 \leq DBT(^{\circ}C) \leq 25$	68	28	25	210	126	28	27	129	128	28	27	91
	No. hours $\Delta T(^{\circ}C) \geq 5$	**167**	**468**	**467**	**466**	**491**	**493**	**496**	**496**	**496**	**496**	**495**	**495**
	No. hours $T(^{\circ}C) \geq 28$	**469**	**261**	**328**	**387**	**415**	**453**	**489**	**502**	**424**	**466**	**491**	**502**
	No. hours $T(^{\circ}C) \geq 32$	**209**	**99**	**139**	**223**	**202**	**272**	**338**	**418**	**214**	**291**	**349**	**423**

4.2.1 STRATEGY A – THERMAL PERFORMANCE ANALYSIS

Under the designed ventilation strategy it can be seen that the classrooms at Haverstock School suffer from considerable summertime overheating with mean temperatures of approximately 30°C across all classrooms under 2004 conditions. Maximums of approximately 38°C are attained under 2004 conditions and are forecast in the 'medium-high' warming scenario simulations to reach a peak of 43.5°C by the 2080s.

Summertime thermal performance - Strategy A

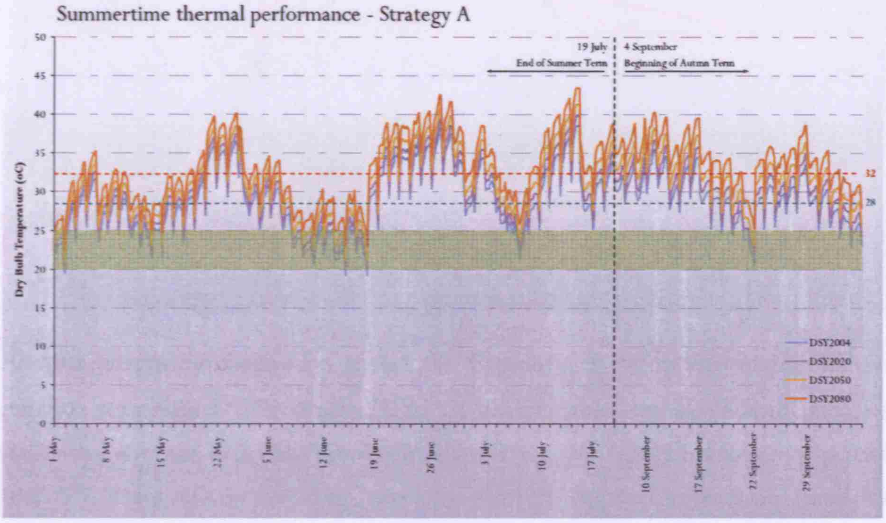


Figure 4-1

Graph showing temperature profile of warmest zone, the southwest-facing ICT room

13-20 June (warmest week) thermal performance

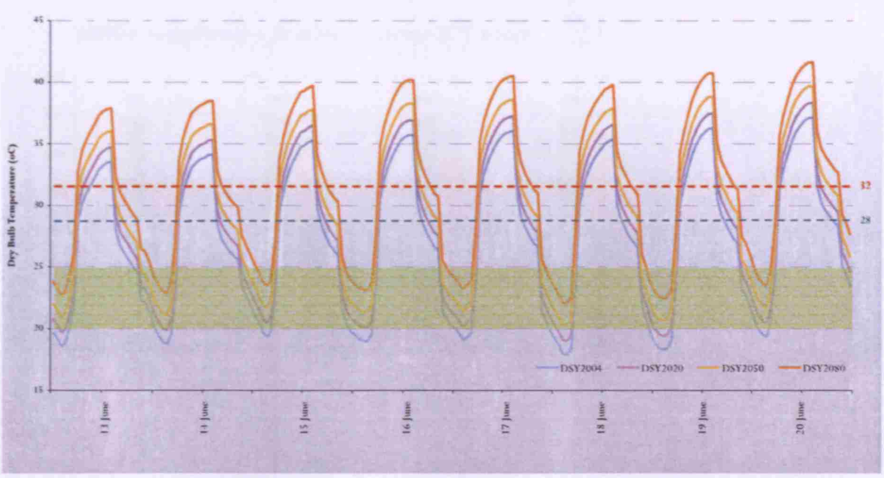


Figure 4-2

Warmer temperatures are experienced for longer in a warming scenario as indicated by widening of the temperature peaks

Analysis of the temperature profile during the warmest week demonstrate that temperatures exceed 28°C for all of the occupied hours during the week. Furthermore, high night-time temperatures (between 20 and 25°C) indicate a small diurnal range and therefore a limited effect of opening the windcatcher for night-purge ventilation. This is especially evident in the temperature profile during the hottest day showing warm temperatures during the night, rapidly increasing with solar gains in the mornings.

20 June (warmest day) thermal performance

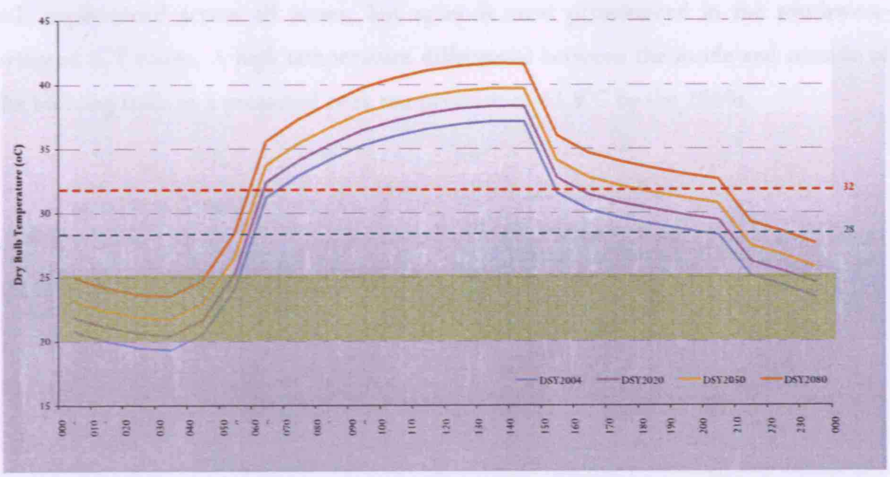


Figure 4-3

Gradients of temperature profile indicate that a significant factor on overheating is low-angle sun in early mornings and afternoons

Another interesting observation is that the frequency of exceedance of the indoor-outdoor temperature differential (ΔT≤5°C) criteria does not significantly increase under the warming scenario. This could indicate that the highly insulative properties (0.294W/m^{2}K) of the building envelope worked counter-productively under a warming scenario in retaining heat within the classrooms.

BB101 compliance - Southwest-facing ICT room

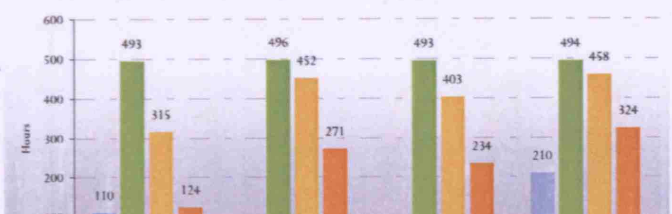


Figure 4-4

BB101 compliance under simulated ventilation strategy
- 20≤T(°C)≤25
- ΔT(°C)≥5
- T(°C)≥28
- T(°C)≥32

4.2.2 STRATEGY B – THERMAL PERFORMANCE ANALYSIS

When a double-opening single-sided ventilation strategy is applied in addition with windcatcher extract and night ventilation, the temperature profile for the summertime period is obtained as shown below. However, despite the provision for additional ventilation (estimated with a 21.22W/m^2 cooling capacity), significant overheating is still experienced across all zones, but again is most pronounced in the southwest-oriented ICT room. A high temperature differential between the inside and outside of the building leads to a projected peak temperature of 42.9°C by the 2080s.

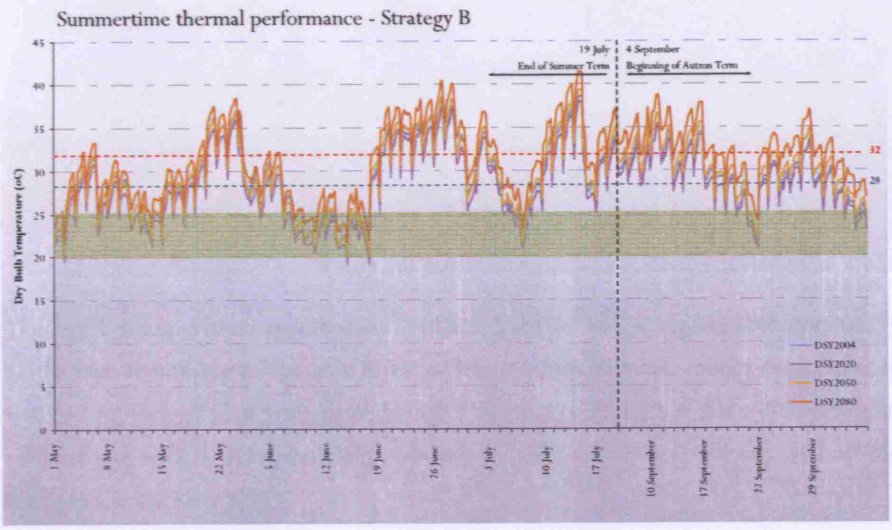


Figure 4-5

Graph showing temperature profile of warmest zone, the southwest-facing ICT room

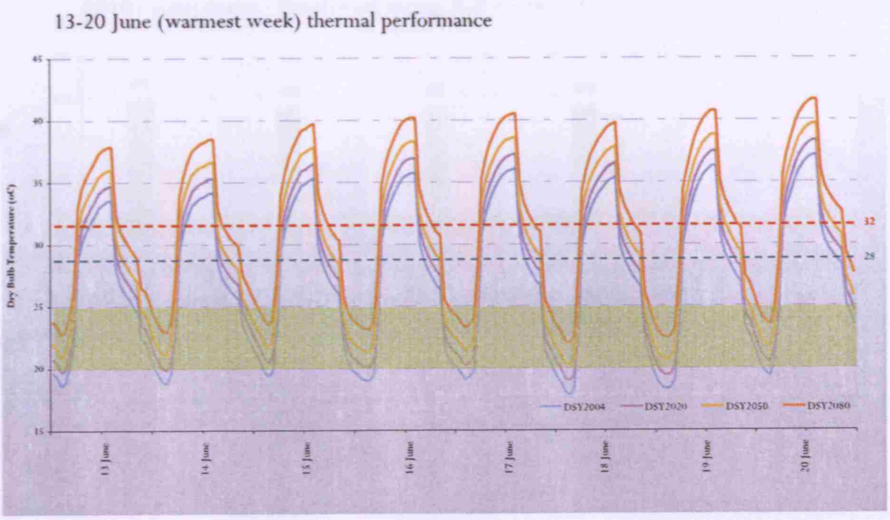


Figure 4-6

Thermal performance of south-facing classroom during warmest week

Thermal performance during the warmest week in the south-facing classroom indicates that in addition to extremely high temperatures, the duration of these conditions will last longer and for a significant part of the occupied day.

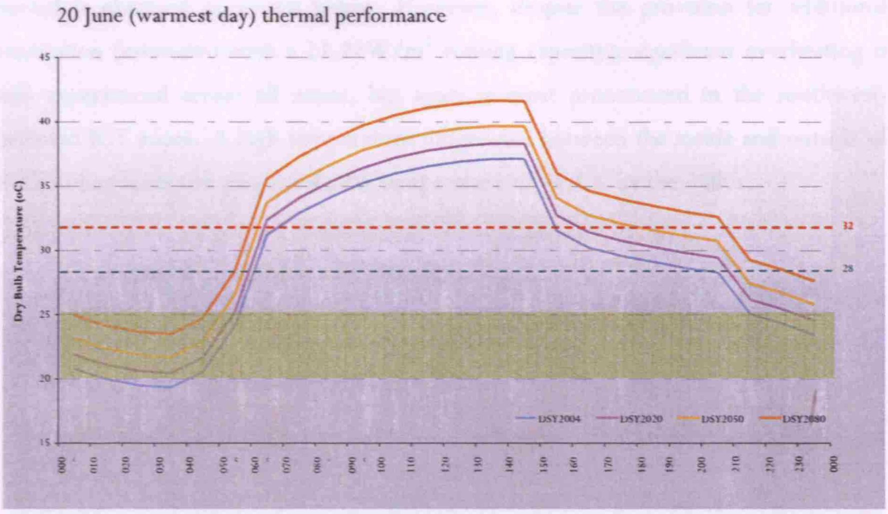


Figure 4-7

Thermal performance of the north-facing classroom during the warmest day

The overheating criteria specified by Building Bulletin 101 is represented graphically below and demonstrates that as a result of the warming climate, indoor temperatures will be low enough to provide some hours of thermal comfort, but this will decrease in conjunction with a corresponding increase in the frequency of hours where the temperature exceeds 32°C.

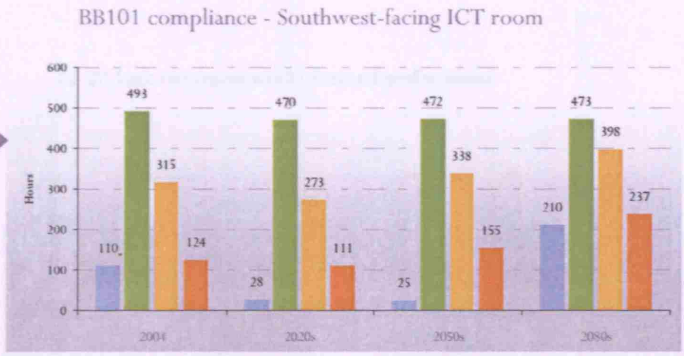


Figure 4-8

BB101 compliance under simulated ventilation strategy
- $20 \leq T(^{\circ}C) \leq 25$
- $\Delta T(^{\circ}C) \geq 5$
- $T(^{\circ}C) \geq 28$
- $T(^{\circ}C) \geq 32$

4.2.3 STRATEGY C – THERMAL PERFORMANCE ANALYSIS

When a double-opening single-sided ventilation strategy is applied in addition with windcatcher extract and night ventilation, the temperature profile for the summertime period is obtained as shown below. However, despite the provision for additional ventilation (estimated with a 21.22W/m^2 cooling capacity), significant overheating is still experienced across all zones, but again is most pronounced in the southwest-oriented ICT room. A high temperature differential between the inside and outside of the building leads to a projected peak temperature of 41.1°C by the 2080s.

Figure 4-9

Graph showing temperature profile of warmest zone, the southwest-facing ICT room

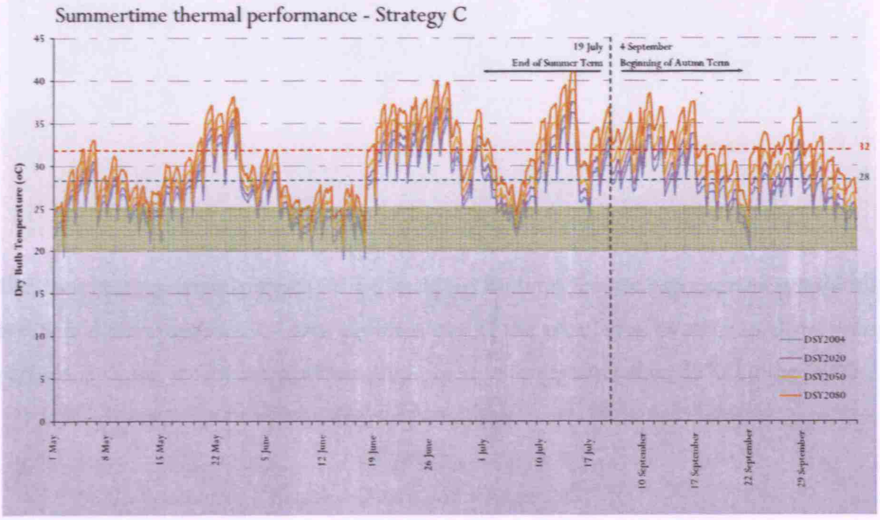
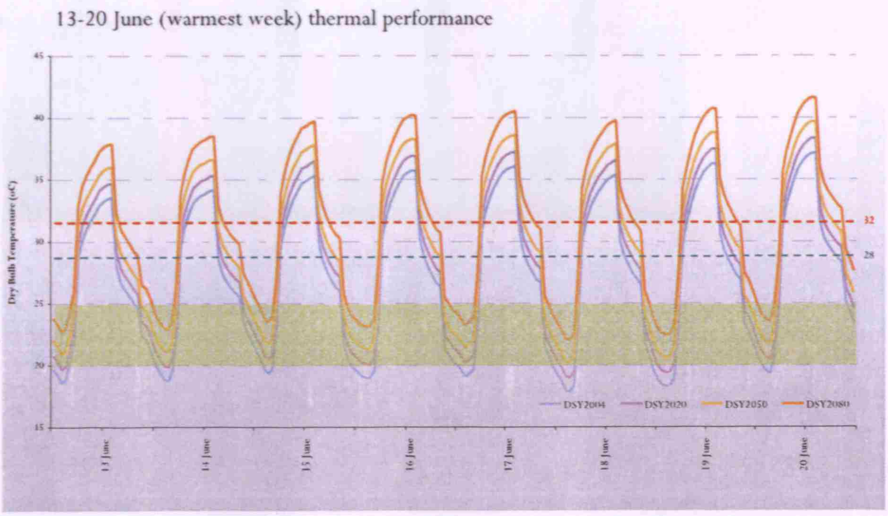


Figure 4-10

Thermal performance of south-facing classroom during warmest week



Again, thermal performance during the warmest week in the south-facing classroom indicates that in addition to extremely high temperatures, the duration of these conditions will last longer and for a significant part of the occupied day.

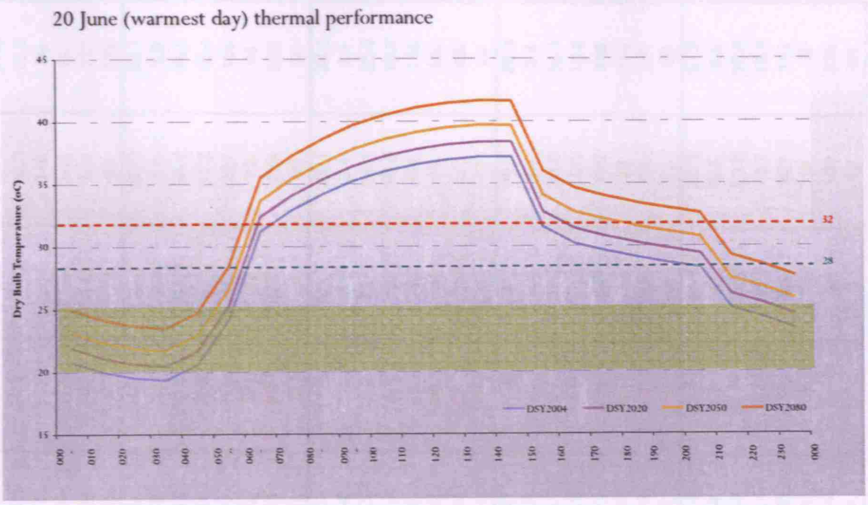


Figure 4-11

Thermal performance of the north-facing classroom during the warmest day

The overheating criteria specified by Building Bulletin 101 is represented graphically below and demonstrates the poor performance of the ventilation strategy in all warming periods, peaking at 324 hours of temperature excesses greater than 32°C by the 2080s.

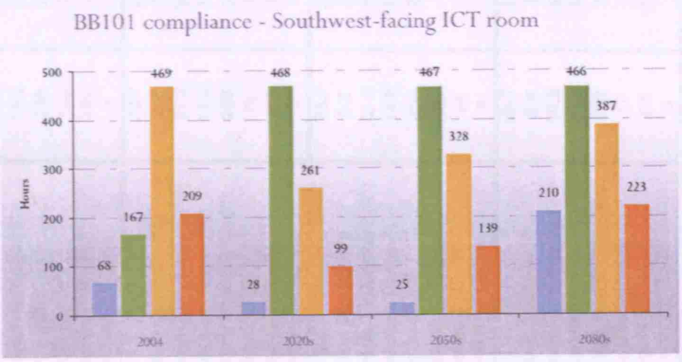


Figure 4-12

BB101 compliance under simulated ventilation strategy
- $20 \le T(^{\circ}C) \le 25$
- $\Delta T(^{\circ}C) \ge 5$
- $T(^{\circ}C) \ge 28$
- $T(^{\circ}C) \ge 32$

4.3 St Mary Magdalene Academy

The zonal mixed-mode St Mary Magdalene Academy was tested under the parameters described in the methodology and the resulting temperature data recorded under each of the different ventilation strategies. A summary of the thermal performance data is shown in Table 4-2.

Table 4-2

Summary of simulation data for 2 zones of classrooms at St Mary Magdalene Academy under operation of designed and adaptive ventilation strategies for 2004, the 2020s, 2050s and 2080s

		South-facing First Floor Typical Classroom				North-facing Second Floor Typical Classroom			
		2004	2020s	2050s	2080s	2004	2020s	2050s	2080s
Strategy A	Mean DBT (ºC)	24.6	25.7	27.1	29.2	24.3	25.5	26.9	29.0
	Standard Deviation (ºC)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	Maximum Temperature (ºC)	32.1	33.2	34.4	36.5	32.8	33.9	35.1	37.0
	Temperature Range (ºC)	15.2	15.4	15.4	15.8	16.0	16.3	16.3	16.5
	No. hours 20≤DBT(ºC)≤25	238	201	134	77	251	211	148	89
	No. hours ΔT(ºC)≥5	**130**	**132**	**162**	**201**	**118**	**118**	**141**	**181**
	No. hours T(ºC)≥28	**102**	**160**	**217**	**334**	**94**	**145**	**197**	**327**
	No. hours T(ºC)≥32	**1**	**11**	**37**	**146**	**1**	**12**	**35**	**129**
Strategy B	Mean DBT (ºC)	23.7	24.6	26.0	28.0	23.7	24.7	26.0	28.1
	Standard Deviation (ºC)	3.2	3.3	3.3	3.3	3.3	3.4	3.4	3.3
	Maximum Temperature (ºC)	31.2	32.4	33.8	35.9	31.8	32.9	34.0	36.0
	Temperature Range (ºC)	14.2	14.6	14.8	15.3	15.0	15.2	15.2	15.4
	No. hours 20≤DBT(ºC)≤25	288	269	223	111	287	261	221	109
	No. hours ΔT(ºC)≥5	**75**	**62**	**72**	**93**	**76**	**63**	**73**	**94**
	No. hours T(ºC)≥28	**57**	**109**	**161**	**246**	**68**	**113**	**158**	**245**
	No. hours T(ºC)≥32	**0**	**4**	**15**	**70**	**0**	**5**	**20**	**82**
Strategy C	Mean DBT (ºC)	23.7	24.7	26.0	28.1	23.7	24.7	26.1	28.1
	Standard Deviation (ºC)	3.3	3.4	3.4	3.4	3.4	3.5	3.4	3.4
	Maximum Temperature (ºC)	31.2	32.2	33.5	35.6	31.9	32.9	34.1	35.9
	Temperature Range (ºC)	14.5	14.7	14.8	15.2	15.3	15.5	15.5	15.7
	No. hours 20≤DBT(ºC)≤25	255	242	199	116	253	238	196	116
	No. hours ΔT(ºC)≥5	**68**	**59**	**79**	**102**	**70**	**65**	**79**	**102**
	No. hours T(ºC)≥28	**56**	**115**	**175**	**258**	**63**	**114**	**171**	**266**
	No. hours T(ºC)≥32	**0**	**2**	**13**	**74**	**0**	**3**	**17**	**84**
Strategy D	Mean DBT (ºC)	23.7	24.7	26.1	28.1	23.9	25.0	26.4	28.4
	Standard Deviation (ºC)	3.3	3.4	3.3	3.3	3.3	3.4	3.4	3.4
	Maximum Temperature (ºC)	30.9	32.2	33.6	35.7	31.6	32.7	34.0	36.1
	Temperature Range (ºC)	14.3	14.7	15.0	15.5	14.8	15.0	15.1	15.6
	No. hours 20≤DBT(ºC)≤25	259	256	194	111	284	247	186	100
	No. hours ΔT(ºC)≥5	**71**	**62**	**81**	**109**	**86**	**80**	**89**	**113**
	No. hours T(ºC)≥28	**52**	**117**	**172**	**254**	**77**	**124**	**175**	**271**
	No. hours T(ºC)≥32	**0**	**2**	**15**	**72**	**0**	**8**	**21**	**98**
Strategy E	Mean DBT (ºC)	23.4	24.4	25.8	27.8	23.1	24.2	25.5	27.5
	Standard Deviation (ºC)	3.4	3.4	3.4	3.4	3.5	3.5	3.5	3.5
	Maximum Temperature (ºC)	30.9	31.9	33.2	35.3	31.5	32.6	33.8	35.6
	Temperature Range (ºC)	14.7	14.7	14.9	15.4	15.7	15.7	15.7	15.9
	No. hours 20≤DBT(ºC)≤25	259	247	216	125	259	252	221	142
	No. hours ΔT(ºC)≥5	**29**	**26**	**48**	**74**	**13**	**13**	**30**	**56**
	No. hours T(ºC)≥28	**49**	**104**	**154**	**244**	**48**	**95**	**139**	**232**
	No. hours T(ºC)≥32	**0**	**0**	**9**	**66**	**0**	**1**	**12**	**60**

4.3.1 STRATEGY A – THERMAL PERFORMANCE ANALYSIS

The designed ventilation strategy of typical classrooms in St Mary Magdalene Academy use the wind-driven localised stack effect to convect heat away from the working plane towards an upper opening as part of a double-opening aperture system.

The current performance of the existing ventilation strategy indicates that it nearly satisfies the criteria for overheating with the exception that the internal-external temperature difference exceeds 5°C for almost 20% of occupied hours during the summer. Furthermore, thermal comfort is provided for more than half the time. The temperature profile of the north-facing classroom on the second floor is presented.

Summertime thermal performance - Strategy A

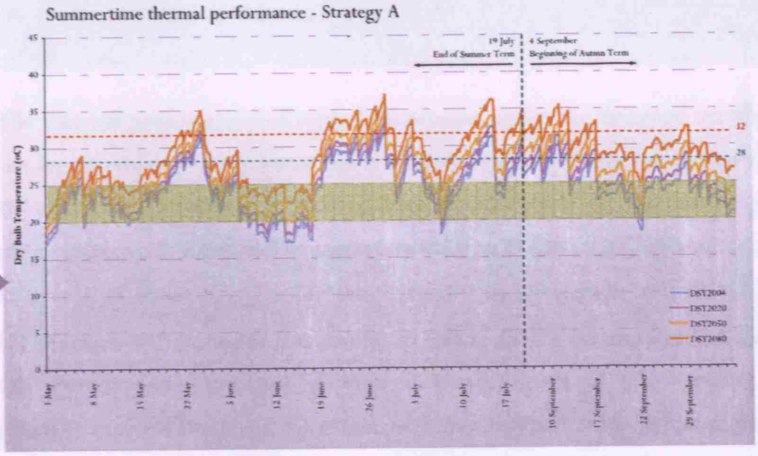


Figure 4-13

Graph showing temperature profile of a north-facing classroom on the second floor

13-20 June (warmest week) thermal performance

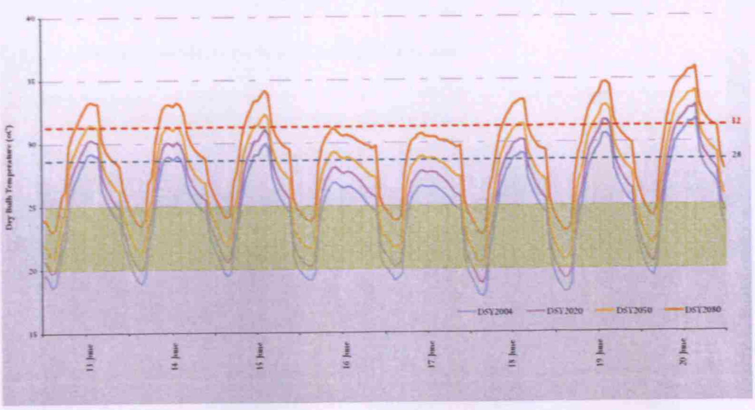


Figure 4-14

Thermal performance of south-facing classroom during warmest week

The temperature behaviour inside the south-facing classroom during the warmest week can be used to readily illustrate that significant overheating above 32°C using the designed ventilation strategy only occurs after the 2050s period and that until then, temperatures during the occupied hours will most likely be stratified in a band between 28 and 32°C during the hottest days, and often between 25 and 30°C otherwise.

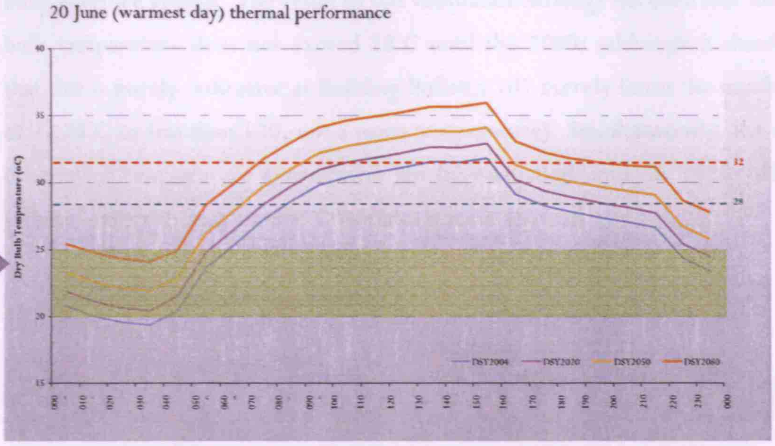


Figure 4-15

Thermal performance of south-facing classroom during hottest day

The thermal performance of typical classrooms under the designed ventilation strategy can be generalised to represent the temperature characteristics as shown below. As can be seen, the provision of thermal comfort decreases in the warming scenario in conjunction with increased temperatures above 28 and 32°C as well as an increasing frequency of hours at which the internal-external temperature difference exceeds 5°C. However, worth noting is that the hours where $\Delta T \geq 5$°C increases at a lesser rate than the corresponding increase in ambient temperatures of the warming scenario. A possible explanation could be effect of heavy thermal mass in the exposed concrete soffit ceilings which would serve so as to absorb heat from resulting external temperature increases.

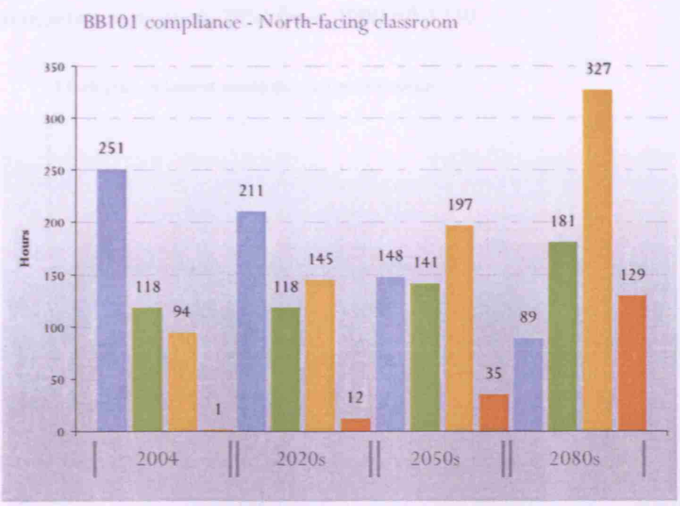


Figure 4-16

BB101 compliance under simulated ventilation strategy
■ 20≤T(°C)≤25
■ ΔT(°C)≥5
■ T(°C)≥28
■ T(°C)≥32

4.3.2 STRATEGY B – THERMAL PERFORMANCE ANALYSIS

Strategy B precribes the increase in openable window area by the employment of a side-hung aperture system. The result of this ventilation strategy has been that the mean dry-bulb temperature does not exceed 28°C until the 2080s (although it should be noted that this is purely indicative as Building Bulletin 101 merely limits the number of hours of T≥28°C to less than 120, not a mean temperature). Simultaneously, the overheating criteria for temperature exceedances are fully satisfied until the 2020s although high internal-external temperature differences remain an issue.

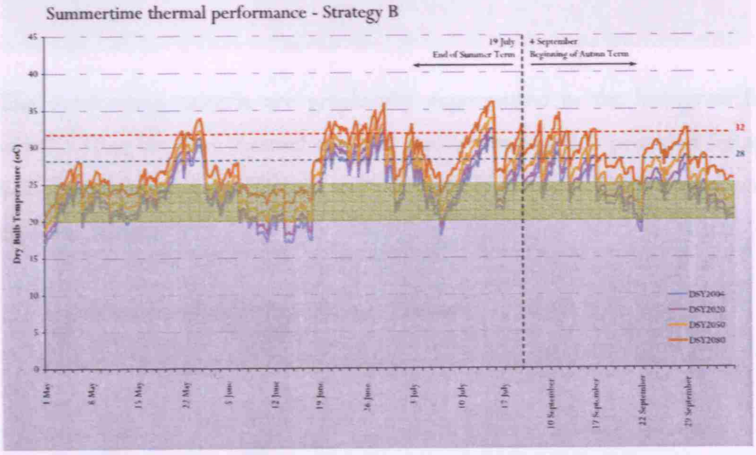


Figure 4-17

Graph showing temperature profile of a north-facing classroom on the second floor

The temperature profile for the warmest week again shows the duration of high temperatures coincident with the occupied period. However, only by the 2050s are temperatures that exceed 28°C an issue, and even then, its duration is only for approximately 4 hours on most hot days, with the exception of 20^{th} June where the temperature exceeds 28°C from 0900 till 1730.

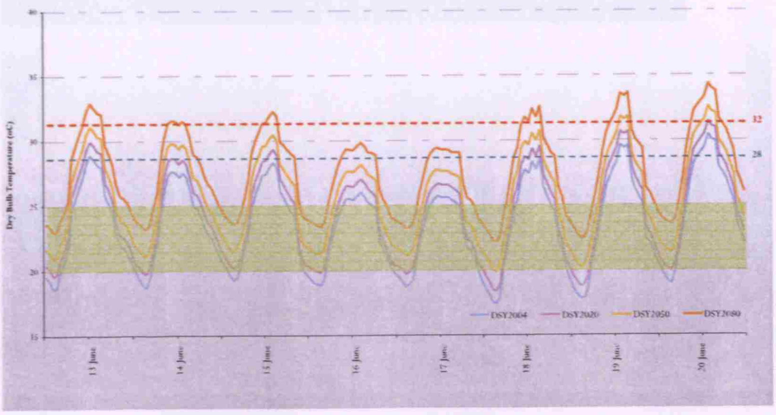


Figure 4-18

Graph showing temperature profile of a south-facing classroom during the warmest week

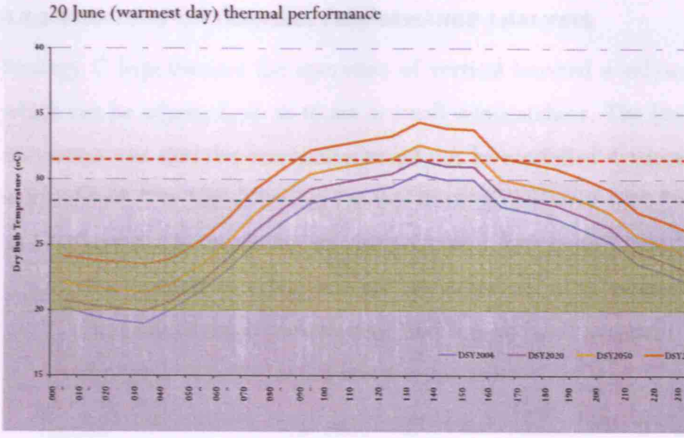


Figure 4-19

Graph showing temperature profile of a south-facing classroom during the hottest day

The overheating criteria are graphically represented in the histogram below. Points worth noting are that thermal comfort under Strategy B is provided for approximately half of summer occupied hours, and the number of hours T≥28°C does not exceed 120 until the 2080s.

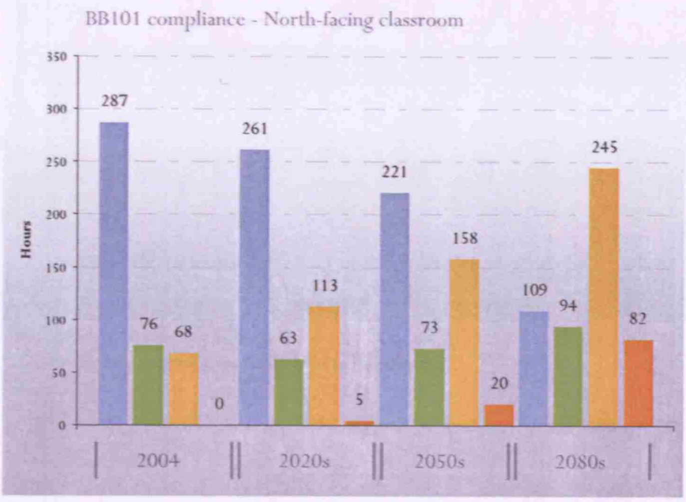


Figure 4-20

BB101 compliance under simulated ventilation strategy
20≤T(°C)≤25
ΔT(°C)≥5
T(°C)≥28
T(°C)≥32

4.3.3 STRATEGY C – THERMAL PERFORMANCE ANALYSIS

Strategy C hypothesises the operation of vertical louvred windows, the orientation of which can be adjusted, so as to act as small windcatchers. The limitation of this in the simulation was that the orientation could not be modelled dynamically and a flat plane was assumed. The key differences to this strategy compared with Strategy B were,

- increase in maximum openable window area from $5.76m^2$ to $7.56m^2$ although this maximum value was not modelled so as to represent real-life physical restrictions such as opening mechanism and occupant discomfort due to draughts. A factor of 0.8 was thus assumed
- a greater control range (start opening at 18°C, fully opened at 28°C) so as to simulate variable window geometry in response to temperature

Figure 4-21

Graph showing temperature profile of a north-facing classroom on the second floor

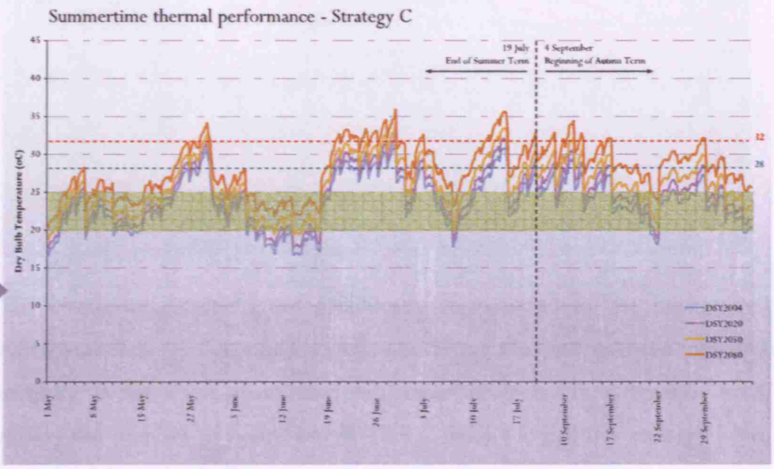
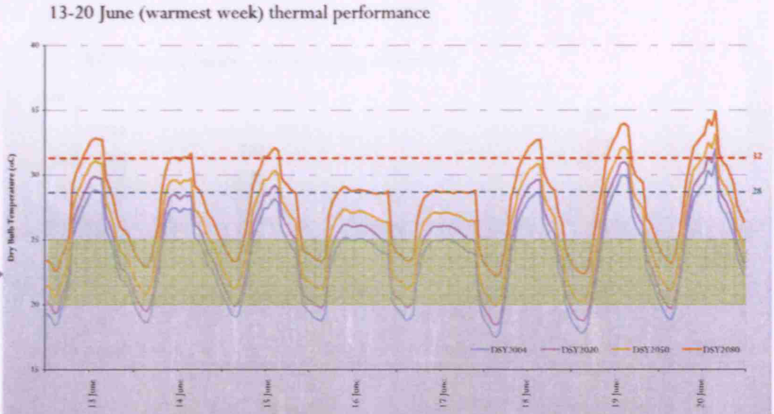


Figure 4-22

Graph showing temperature profile of a south-facing classroom during the warmest week



As expected from a greater openable area, the simulation of vertical sash/louvred-windows resulted in a marked improvement upon the designed ventilation strategy (A), with a 1°C reduction in mean and maximum temperatures. In addition, the number of hours for which $\Delta T \geq 5°C$ were halved in Strategy C compared with the designed ventilation strategy, A. Moreover, dry-bulb temperatures greater than 28 and 32°C are reduced in frequency by more than half.

Analysis of the temperature profile for the hottest day, 20th June, indicates much the same behaviour as Strategy B but with a peak temperature occurring approximately one hour later.

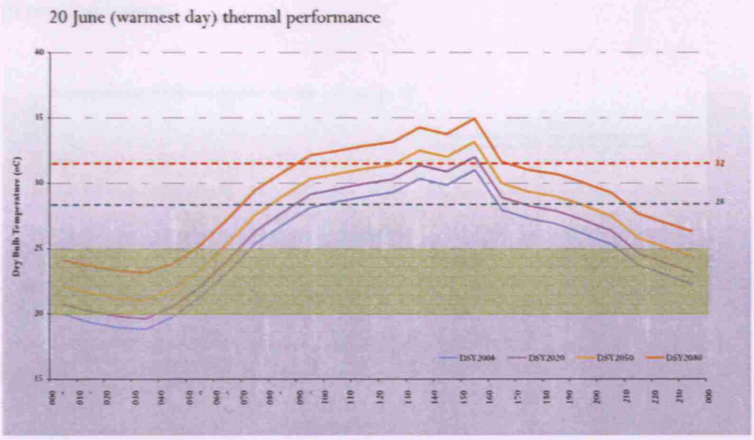


Figure 4-23

Graph showing temperature profile of a south-facing classroom during the hottest day

The overheating criteria are graphically represented in the histogram below. The efficacy of Strategy C is summarised as satisfying the never-exceed temperature of 32°C until the 2020s where mean temperatures are projected to increase by 4.4°C to 28.1°C, raising the number of hours where $T \geq 5°C$ from 63, had this strategy been adopted, in 2004 to 266 by the 2080s.

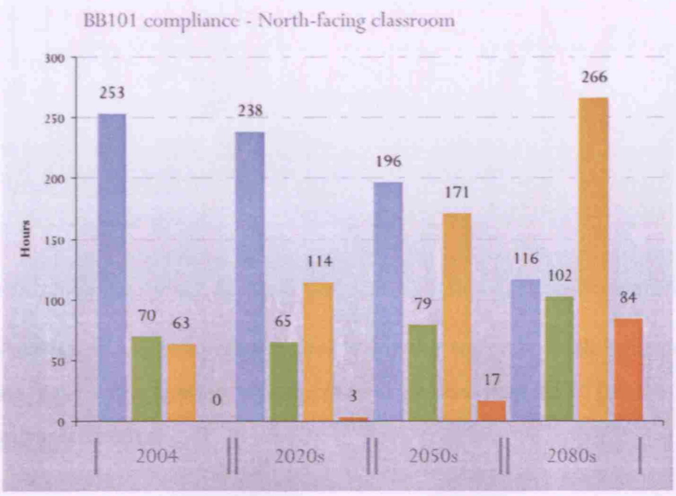


Figure 4-24

BB101 compliance under simulated ventilation strategy
- $20 \leq T(°C) \leq 25$
- $\Delta T(°C) \geq 5$
- $T(°C) \geq 28$
- $T(°C) \geq 32$

4.3.4 STRATEGY D – THERMAL PERFORMANCE ANALYSIS

Strategy D prescribed the use of cross ventilation by use of high-level vents on the inner walls of each classroom, to facilitate air movement out of the densely-occupied classrooms into the low-pressured circulation areas such as corridors, and atria. Overall, Strategy D seems to provide similar performance to Strategy C whereby mean temperatures in the 2080s are forecast to increase by 4.4°C to 28.1±3.3°C.

The summertime performance of the north-facing classrooms on the second floor are presented below.

Summertime thermal performance - Strategy D

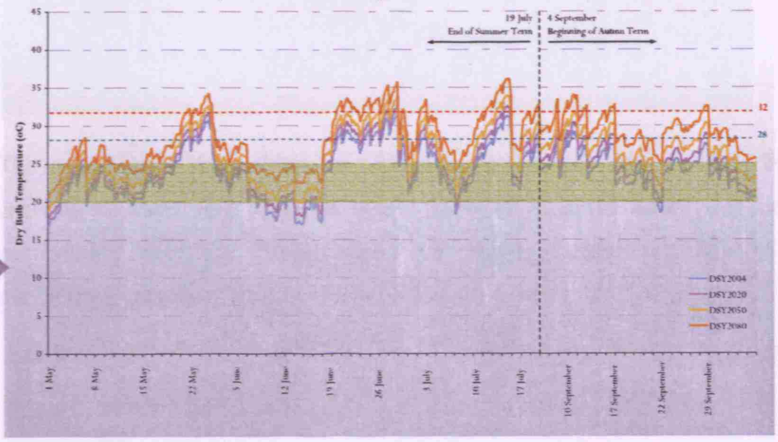


Figure 4-25

Graph showing temperature profile of a north-facing classroom on the second floor

13-20 June (warmest week) thermal performance

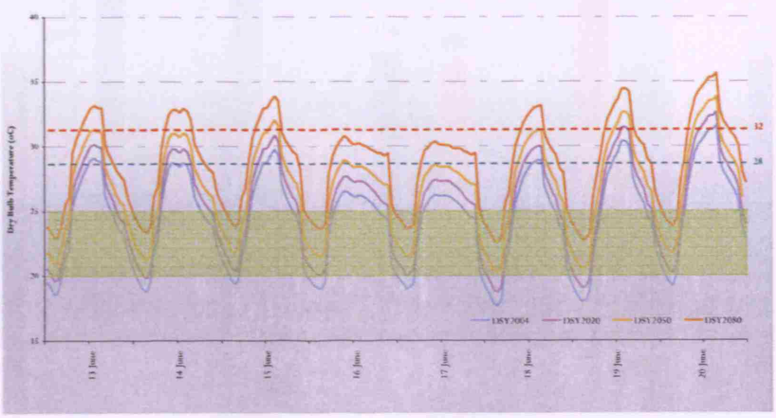


Figure 4-26

Graph showing temperature profile of a south-facing classroom during the warmest week

Analysis of the temperature profile for the warmest week indicates that by the 2080s, six days will experience temperatures greater than 32°C for the duration of the daily occupied hours.

The temperature profile for the hottest day of the year similarly shows a steady increase in temperatures during the day, peaking at 1600 hrs before falling sharply (4°C drop in 1 hour) as the occupancy rates in the classrooms reduce to zero.

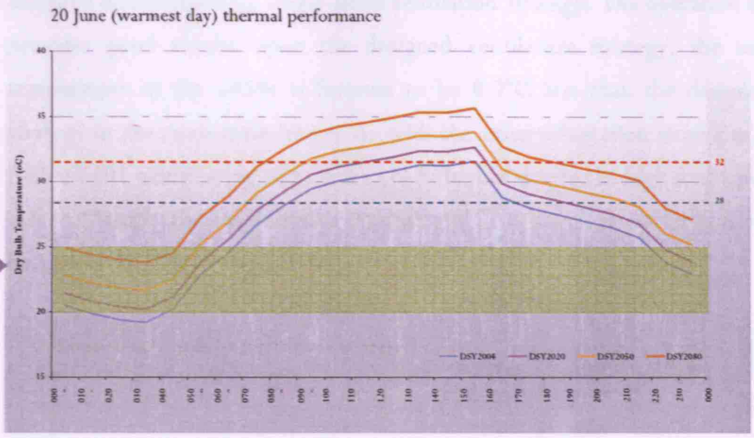


Figure 4-27

Graph showing temperature profile of a south-facing classroom during the hottest day

The temperature characterisation of Strategy D, in line with Building Bulletin 101 criteria, indicates that although nearly 50% of occupied hours will be thermally comfortable until the 2050s, where the strategy completely fails to meet the overheating criteria.

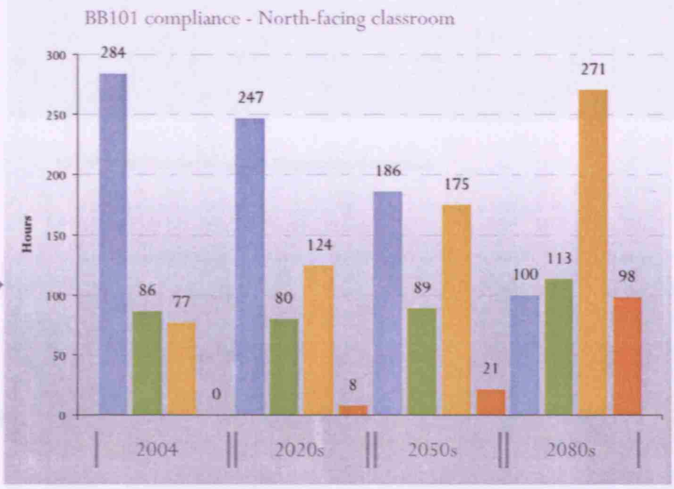


Figure 4-28

BB101 compliance under simulated ventilation strategy
- 20≤T(°C)≤25
- ΔT(°C)≥5
- T(°C)≥28
- T(°C)≥32

4.3.5 STRATEGY E – THERMAL PERFORMANCE ANALYSIS

Strategy E examined the effect of a split-duct roof-mounted ventilator to assist in cold air penetration as well as cross-ventilative heat extract working in conjunction with the designed double-opening single-sided ventilation strategy. The operation of the strategy provides good results upon the designed ventilation strategy; the mean dry-bulb temperature in the 2080s is forecast to be 8.7°C less than the designed ventilation strategy in the same time-frame. As with the other adaptation strategies, the Building Bulletin 101 overheating criteria are not fully met due to the high frequency of internal-external temperature differences exceeding 5°C, although the strategy is resilient in not exceeding 32°C until the 2050s.

Summertime thermal performance - Strategy E

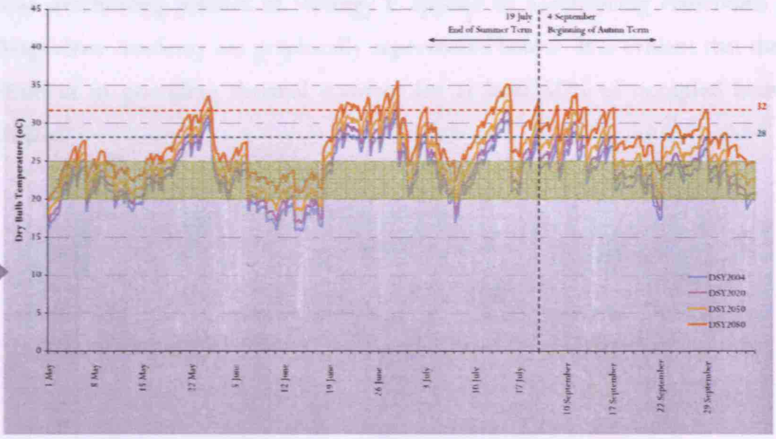


Figure 4-30

Graph showing temperature profile of a north-facing classroom on the second floor

13-20 June (warmest week) thermal performance

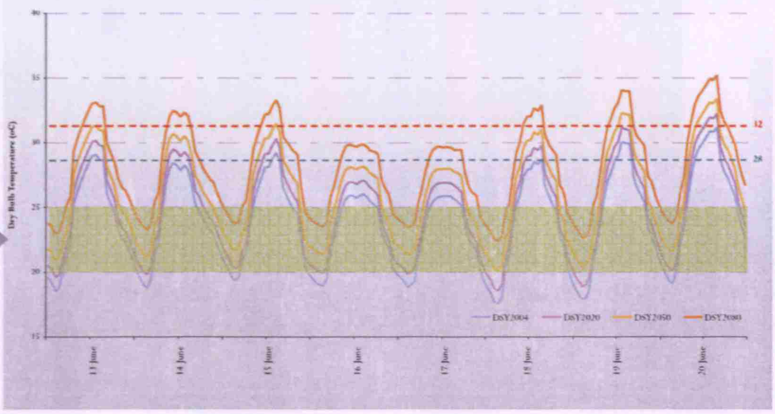


Figure 4-31

Graph showing temperature profile of a south-facing classroom during the warmest week

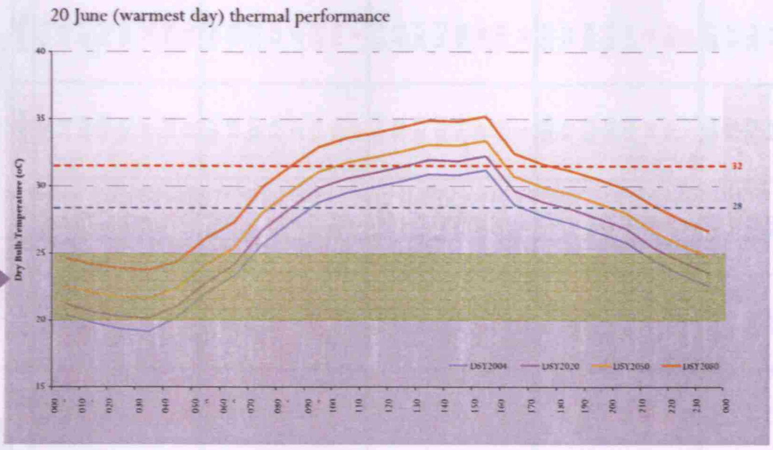


Figure 4-32

Graph showing temperature profile of a south-facing classroom during the hottest day

The overheating profiles of Strategy E applied to north-facing classrooms in St Mary Magdalene Academy are graphically represented below. It is evident that the strategy is resilient in providing thermal comfort for at least 50% of occupied hours until the 2080s.

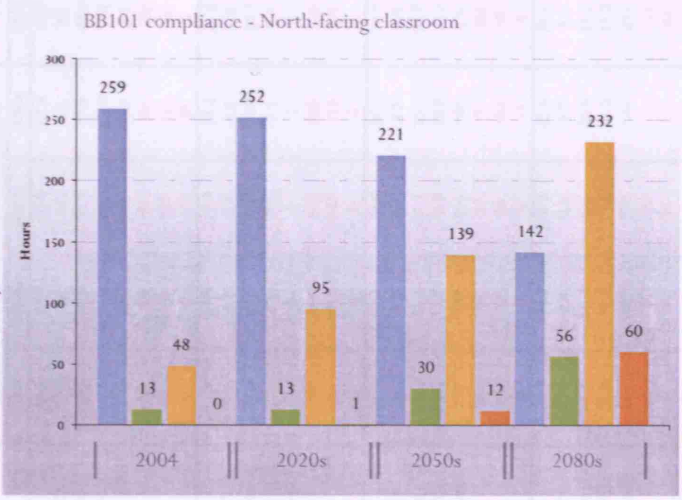


Figure 4-33

BB101 compliance under simulated ventilation strategy
- $20 \le T(^{\circ}C) \le 25$
- $\Delta T(^{\circ}C) \ge 5$
- $T(^{\circ}C) \ge 28$
- $T(^{\circ}C) \ge 32$

4.4 Paddington Academy

The designed ventilation strategy as well as adaptation measures to mitigate against summertime overheating were simulated using weather files corresponding to the 'medium-high' warming scenario as outlined by UKCIP02. The data was analysed as described and is presented below.

Table 4-3

Summary of simulation data for 3 zones of classrooms at Paddington Academy under operation of designed and adaptive ventilation strategies for 2004, the 2020s, 2050s and 2080s

		Ground Floor Northeast-facing Classroom				First Floor Southwest-facing ICT Room				First Floor Southwest-facing Classroom			
		2004	2020s	2050s	2080s	2004	2020s	2050s	2080s	2004	2020s	2050s	2080s
Strategy A	Mean DBT (°C)	23.5	24.5	25.6	27.2	25.0	25.9	27.1	28.7	24.1	25.1	26.2	27.8
	Standard Deviation (°C)	2.9	3.0	3.0	3.2	3.0	3.1	3.1	3.3	3.0	3.1	3.2	3.3
	Maximum Temperature (°C)	30.0	30.9	32.0	33.8	32.3	33.2	34.3	35.9	31.3	32.3	33.4	35.1
	Temperature Range (°C)	12.5	12.8	12.9	13.8	13.6	13.6	13.8	14.5	13.6	13.7	14.0	14.7
	No. hours 20≤DBT(°C)≤25	274	267	211	138	253	197	141	81	275	244	171	116
	No. hours ΔT(°C)≥5	**77**	**65**	**61**	**55**	**182**	**159**	**148**	**133**	**103**	**95**	**87**	**82**
	No. hours T(°C)≥28	**35**	**70**	**137**	**219**	**106**	**146**	**206**	**306**	**61**	**111**	**166**	**246**
	No. hours T(°C)≥32	**0**	**0**	**1**	**25**	**1**	**7**	**27**	**92**	**0**	**1**	**14**	**58**
Strategy B	Mean DBT (°C)	27.5	27.6	27.9	28.3	27.9	28.1	28.3	28.7	27.6	27.8	28.1	28.4
	Standard Deviation (°C)	0.5	0.6	0.8	0.9	0.6	0.7	0.8	0.9	0.6	0.7	0.8	0.9
	Maximum Temperature (°C)	29.3	29.5	29.8	30.2	29.7	30.2	30.8	31.6	29.6	30.1	30.7	31.5
	Temperature Range (°C)	2.8	2.9	3.1	3.3	2.7	3.1	3.6	4.2	3.0	3.4	3.9	4.6
	No. hours 20≤DBT(°C)≤25	0	0	0	0	0	0	0	0	0	0	0	0
	No. hours ΔT(°C)≥5	**40**	**94**	**151**	**225**	**125**	**171**	**232**	**328**	**82**	**122**	**171**	**252**
	No. hours T(°C)≥28	**356**	**306**	**246**	**175**	**367**	**327**	**267**	**187**	**360**	**315**	**250**	**178**
	No. hours T(°C)≥32	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Strategy C	Mean DBT (°C)	22.8	23.7	24.9	26.5	24.5	25.4	26.5	28.2	23.5	24.5	25.6	27.2
	Standard Deviation (°C)	2.9	3.0	3.1	3.2	3.0	3.1	3.1	3.3	3.0	3.1	3.2	3.3
	Maximum Temperature (°C)	29.1	30.1	31.2	33.1	31.7	32.6	33.8	35.4	30.7	31.6	32.8	34.4
	Temperature Range (°C)	12.0	12.5	12.9	13.3	13.3	13.6	13.9	14.2	13.3	13.7	13.9	14.3
	No. hours 20≤DBT(°C)≤25	283	264	244	166	270	233	164	107	273	258	211	138
	No. hours ΔT(°C)≥5	**29**	**16**	**10**	**7**	**134**	**113**	**105**	**93**	**61**	**54**	**47**	**36**
	No. hours T(°C)≥28	**12**	**34**	**98**	**192**	**83**	**121**	**179**	**267**	**34**	**86**	**135**	**223**
	No. hours T(°C)≥32	**0**	**0**	**0**	**13**	**0**	**3**	**20**	**72**	**0**	**0**	**5**	**36**
Strategy D	Mean DBT (°C)	22.4	23.3	24.3	25.6	24.2	25.1	26.2	27.8	23.2	24.2	25.3	26.9
	Standard Deviation (°C)	2.7	2.8	2.8	2.7	2.9	3.0	3.1	3.2	3.0	3.0	3.1	3.2
	Maximum Temperature (°C)	27.7	28.4	29.3	30.6	31.3	32.2	33.2	24.8	30.2	31.2	32.2	33.8
	Temperature Range (°C)	10.6	11.0	11.2	11.2	13.0	13.3	13.5	13.7	13.1	13.6	13.6	13.9
	No. hours 20≤DBT(°C)≤25	273	261	200	144	246	181	130	75	272	244	173	116
	No. hours ΔT(°C)≥5	**20**	**8**	**3**	**1**	**116**	**105**	**88**	**76**	**48**	**39**	**26**	**18**
	No. hours T(°C)≥28	**0**	**8**	**31**	**121**	**64**	**107**	**163**	**253**	**24**	**60**	**118**	**204**
	No. hours T(°C)≥32	**0**	**0**	**0**	**0**	**0**	**1**	**8**	**53**	**0**	**0**	**1**	**21**
Strategy E	Mean DBT (°C)	22.4	22.8	23.2	23.6	23.1	23.4	23.7	23.9	22.6	23.0	23.4	23.7
	Standard Deviation (°C)	1.8	1.7	1.4	0.9	1.4	1.1	0.8	0.5	1.7	1.5	1.2	0.7
	Maximum Temperature (°C)	25.6	26.1	26.6	27.2	27.0	27.5	28.2	29.1	26.5	27.0	27.7	20.4
	Temperature Range (°C)	6.6	7.1	7.6	7.5	8.0	8.1	7.9	7.7	7.5	8.0	8.4	8.1
	No. hours 20≤DBT(°C)≤25	431	461	495	523	497	512	524	524	457	491	511	524
	No. hours ΔT(°C)≥5	**43**	**33**	**17**	**5**	**138**	**113**	**84**	**53**	**67**	**59**	**47**	**33**
	No. hours T(°C)≥28	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**1**
	No. hours T(°C)≥32	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

4.4.1 STRATEGY A – THERMAL PERFORMANCE ANALYSIS

The designed strategy uses a fan-assisted low-pressure ventilation system from a ground-coupled source in a 1 metre deep undercroft beneath the building. Air is supplied at a maximum of $0.45m^3/s$ through ductwork within the façade, and exits through high-level vents into circulation areas. This was modelled in TAS using inter-zonal air movement (IZAM) at a corresponding mass flow rate of 0.54kg/s and predicted to perform in the southwest-facing classrooms as depicted in the figure below. Based on this, the designed strategy seems satisfactory in preventing occurrences of temperatures above 32°C until the 2080s. Significantly, a large number of occupied hours are indicated to be at a temperature which is thermally comfortable.

Summertime thermal performance - Strategy A

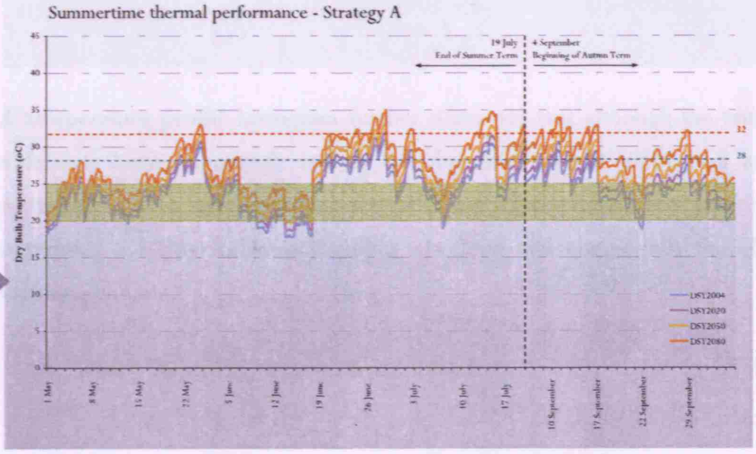


Figure 4-34

Graph showing temperature profile of a northeast-facing classroom on the ground floor

13-20 June (warmest week) thermal performance

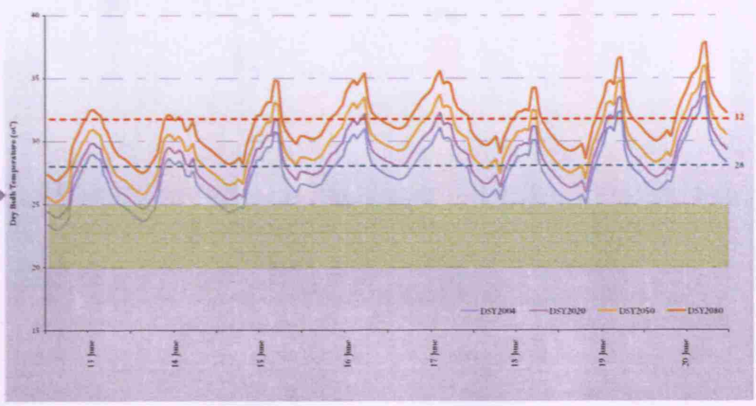


Figure 4-35

Graph showing temperature profile of a southwest-facing classroom on the first floor during the warmest week

Interesting to note from the thermal performance of the southwest-facing classrooms during the warmest week is that diurnal temperature variation is only ~10°C for most nights which could imply that night ventilation has a reduced effect on lowering daytime temperatures. This could be corroborated by the high temperatures experienced during the night of the 16th/17th where the following day experiences similarly warm temperatures.

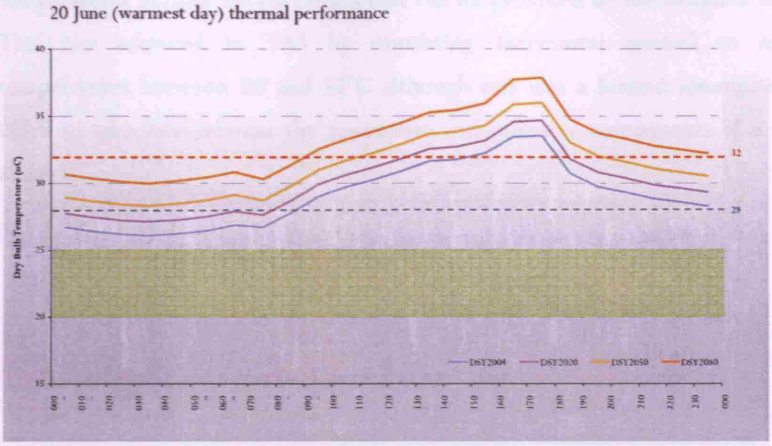


Figure 4-36

Graph showing temperature profile of a southwest-facing classroom on the first floor during the hottest day

A temperature profile histogram further illustrates that although the temperature difference between outside and in falls by only a small proportion across the warming periods, overheating above 28°C and 32°C increase to a greater extent, suggesting a highly insulative building envelope that compounds the effect of a warming climate.

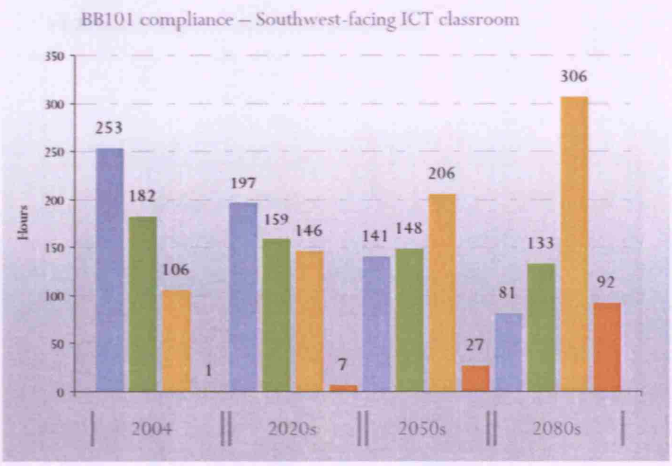


Figure 4-37

BB101 compliance under simulated ventilation strategy
- $20 \leq T(^{\circ}C) \leq 25$
- $\Delta T(^{\circ}C) \geq 5$
- $T(^{\circ}C) \geq 28$
- $T(^{\circ}C) \geq 32$

4.4.2 STRATEGY B – THERMAL PERFORMANCE ANALYSIS

Strategy B simulates a 'comfort cooling' adaptation strategy, by fan coil units for example, whereby proportional control is exercised over the cooling output when temperatures exceed the maximum that can be provided by the designed strategy. This was achieved in TAS by simulating thermostat control to maintain temperatures between 28 and 32°C although this was a limited assumption as it failed to take into account the convective and radiative components of a cooling emitter.

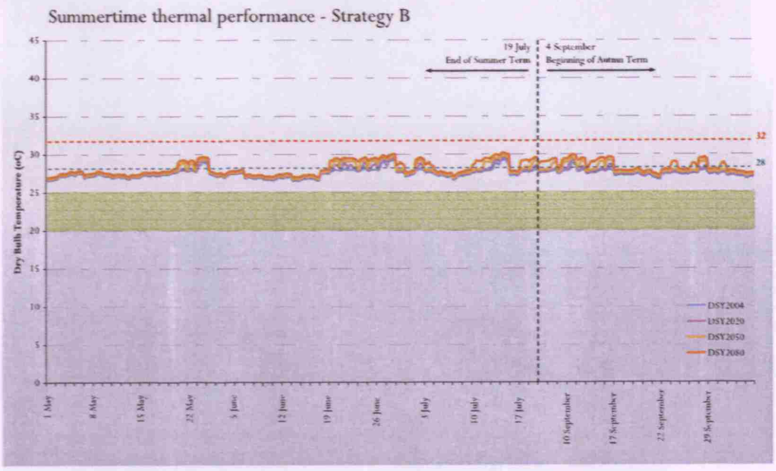


Figure 4-38

Graph showing temperature profile of a northeast-facing classroom on the ground floor

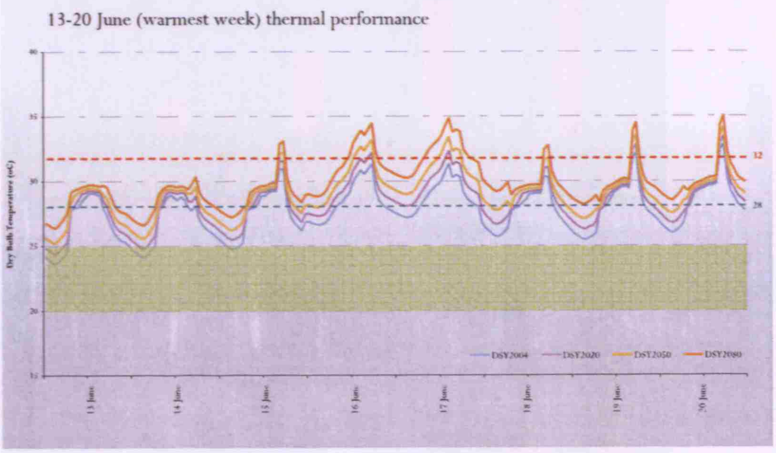


Figure 4-39

Graph showing temperature profile of a southwest-facing classroom on the first floor during the warmest week

The thermal performance of the adaptation strategy is as expected; close control during occupied hours with significantly reduced temperatures overnight. Interesting to note are that the peak temperatures are short-lived, indicated by narrow peaks, and suggesting that the thermostat may operate on a lag in compensating for incidences of high temperatures. Additionally, the peak temperatures occur in conjunction with the switching off of comfort cooling after the classroom occupancies fall to zero, and may also be the result of low-angle solar gains during the early evening.

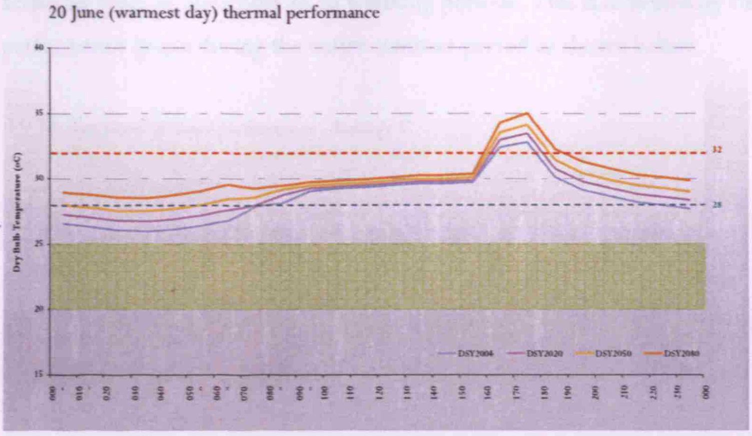


Figure 4-40

Graph showing temperature profile of a southwest-facing classroom on the first floor during the hottest day

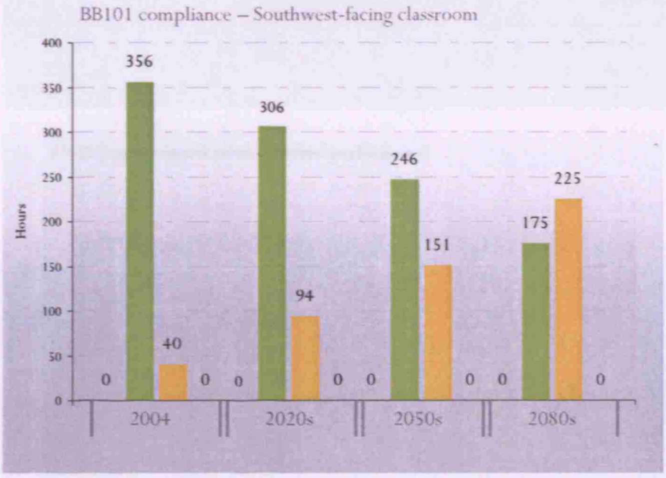


Figure 4-41

BB101 compliance under simulated ventilation strategy
20≤T(°C)≤25
ΔT(°C)≥5
T(°C)≥28
T(°C)≥32

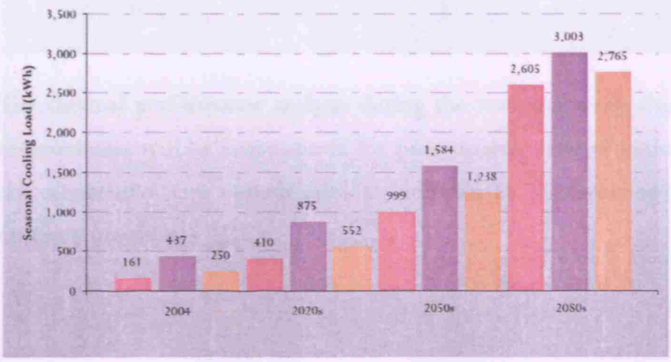


Figure 4-42

Seasonal Cooling Load profile

GF northeast-facing classroom
1F southwest-facing ICT room
1F southwest-facing classroom

The profile of the cooling loads necessary to maintain temperature between 28 and 32°C are indicative only as this works in conjunction with the designed strategy.

4.4.3 STRATEGY C – THERMAL PERFORMANCE ANALYSIS

The adaptation strategy of introducing night-ventilation to the classrooms during unoccupied hours had the desired effect of reducing the extent of overheating across all types of classroom in all warming periods. This is indicated by the thermal performance graph during the entire summer period as shown below.

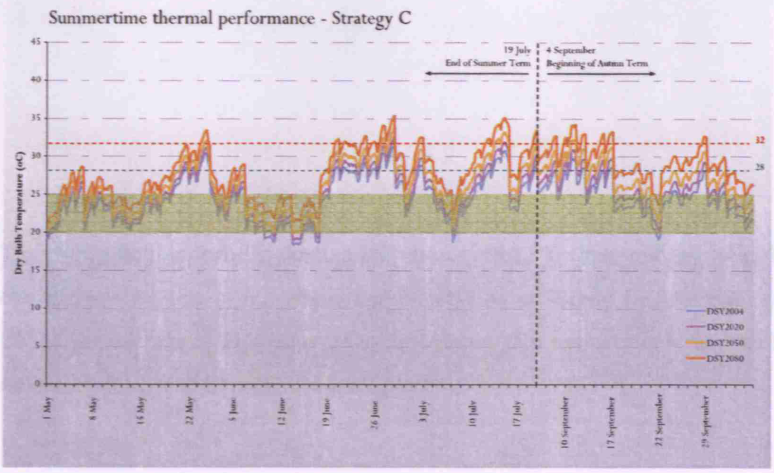


Figure 4-43

Graph showing temperature profile of a northeast-facing classroom on the ground floor

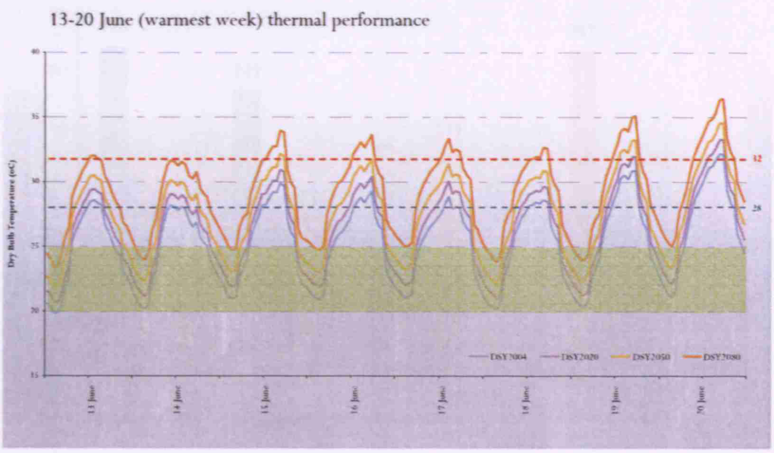


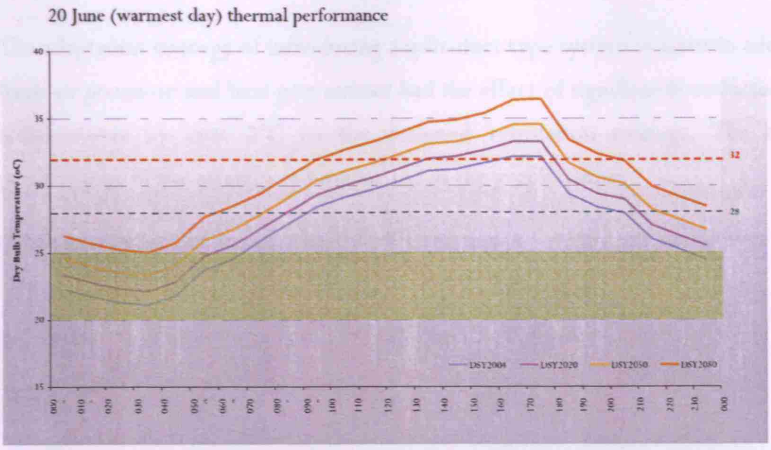
Figure 4-44

Graph showing temperature profile of a southwest-facing classroom on the first floor during the warmest week

The thermal performance analysis during the warmest week also shows that cool temperatures will be encountered for progressively shorter periods of time under the consecutive test periods (this is indicated by a narrowing of the trough of temperatures below 25°C).

Figure 4-45

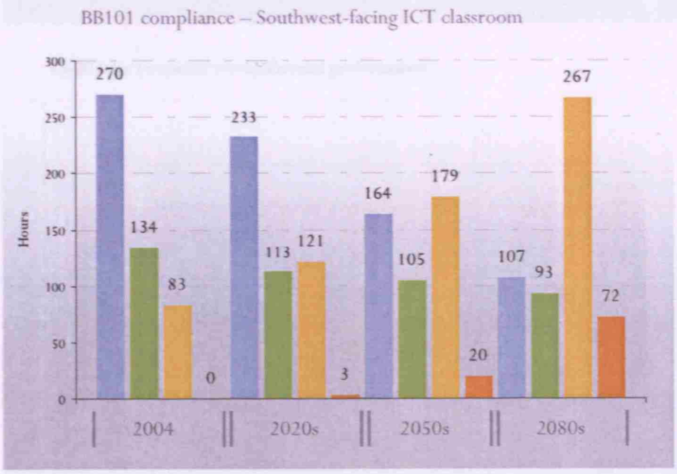
Graph showing temperature profile of a southwest-facing classroom on the first floor during the hottest day



The temperature profile histogram shows that, if assessed by the T≥28°C overheating criteria only, adaptation strategy C will only be effective until the 2050s period where significant warming above this temperature, and with more extreme peaks, will become commonplace.

Figure 4-46

BB101 compliance under simulated ventilation strategy
- 20≤T(°C)≤25
- ΔT(°C)≥5
- T(°C)≥28
- T(°C)≥32



4.4.4 STRATEGY D – THERMAL PERFORMANCE ANALYSIS

The adaptation strategy of introducing a split-duct type system to assist in additional fresh air provision and heat gain extract had the effect of significantly reducing mean temperatures by upto 2°C on the designed ventilation strategy. The thermal performance of the strategy is summarised in the graph below.

Summertime thermal performance - Strategy D

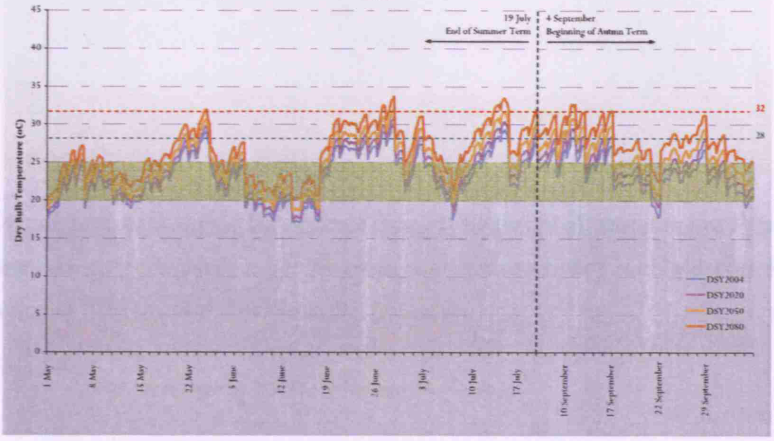


Figure 4-47

Graph showing temperature profile of a northeast-facing classroom on the ground floor

13-20 June (warmest week) thermal performance

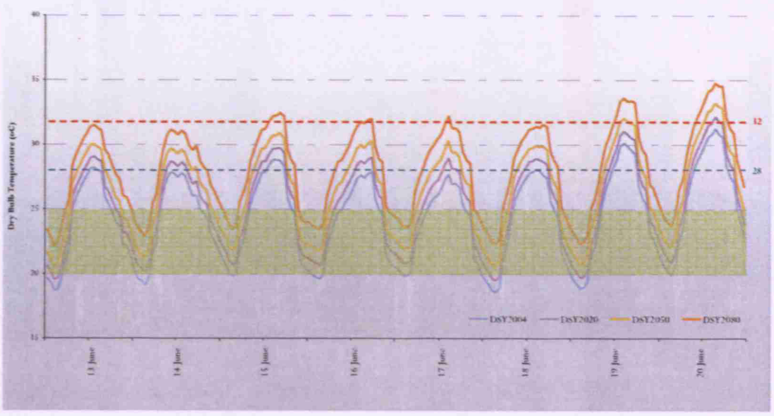


Figure 4-48

Graph showing temperature profile of a southwest-facing classroom on the first floor during the warmest week

Data from simulation indicates that, had the split-duct system been installed as the designed ventilation strategy, then the BB101 criteria for overheating would be entirely satisfied in the ground floor northeast-facing classrooms until the 2020s period. Beyond the 2020s, the incidence of high temperatures would become more commonplace although the strategy would demonstrate resilience in maintaining temperatures above 28°C for less than 120 hours until the 2080s period.

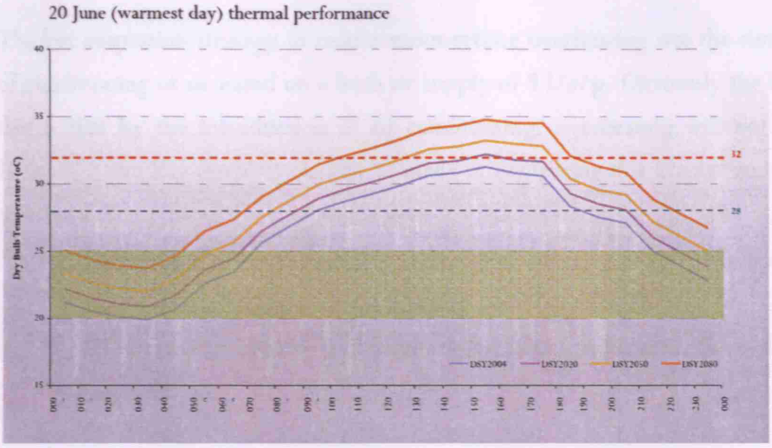


Figure 4-49

Graph showing temperature profile of a southwest-facing classroom on the first floor during the hottest day

As can be seen from the histogram below, occurrences of temperatures above 28°C are forecast to become more commonplace in conjunction with a decrease in the number of hours of thermal comfort provision.

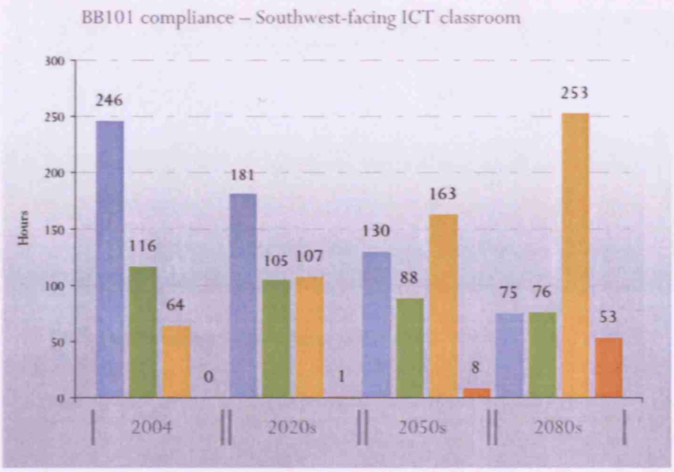


Figure 4-50

BB101 compliance under simulated ventilation strategy
- 20≤T(°C)≤25
- ΔT(°C)≥5
- T(°C)≥28
- T(°C)≥32

4.4.5 STRATEGY E – THERMAL PERFORMANCE ANALYSIS

The last adaptation strategy to reduce summertime overheating was the simulation of conditioning of air based on a fresh air supply of 8 l/s/p. Obviously the logic in this is that by the introduction of air conditioning, overheating will not occur. However, two key observations can be made in comparing this adaptation strategy to others:

- The number of hours ΔT≤5°C to show the difficulty of indoor temperature control in a warming external scenario
- The increase in cooling load required due to this to maintain thermal comfort

Summertime thermal performance - Strategy E

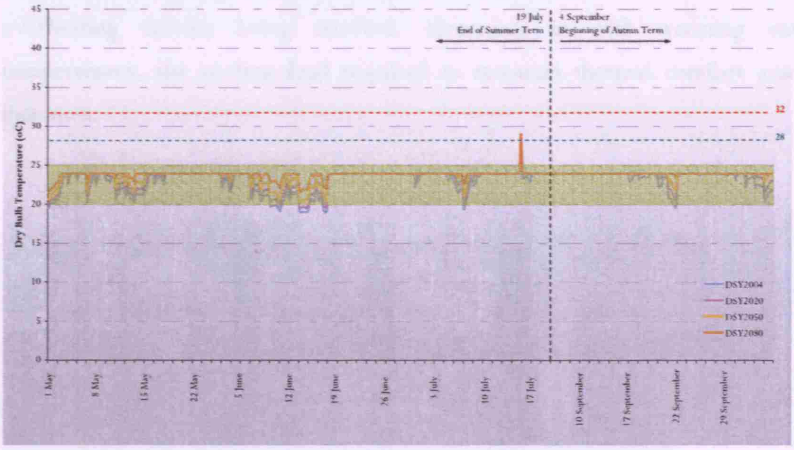


Figure 4-51

Graph showing temperature profile of a northeast-facing classroom on the ground floor

13-20 June (warmest week) thermal performance

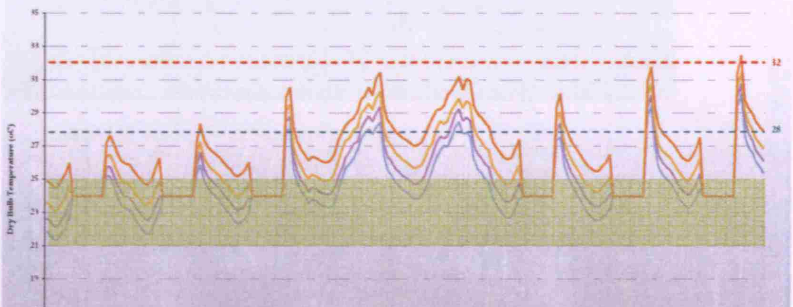


Figure 4-52

Graph showing temperature profile of a southwest-facing classroom on the first floor during the warmest week

Analysis of the warmest week shows that although set to provide an internal temperature of between 20 and 25°C, overheating above this does occur. An explanation for this can be deduced by noting that high temperatures occur mostly outside the period of occupancy, when the classrooms are unconditioned.

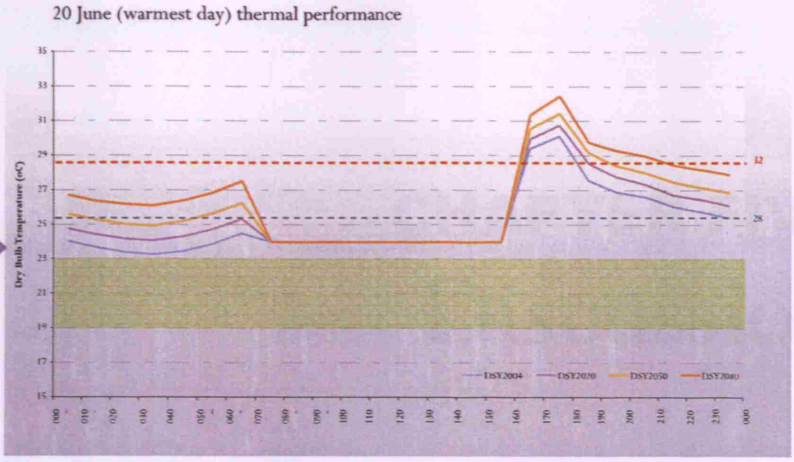


Figure 4-53

Graph showing temperature profile of a southwest-facing classroom on the first floor during the hottest day

Thermal comfort is provided under all warming scenarios with two of the three overheating criteria being satisfied. However, as with warming external temperatures, the cooling load required to maintain thermal comfort gradually increases.

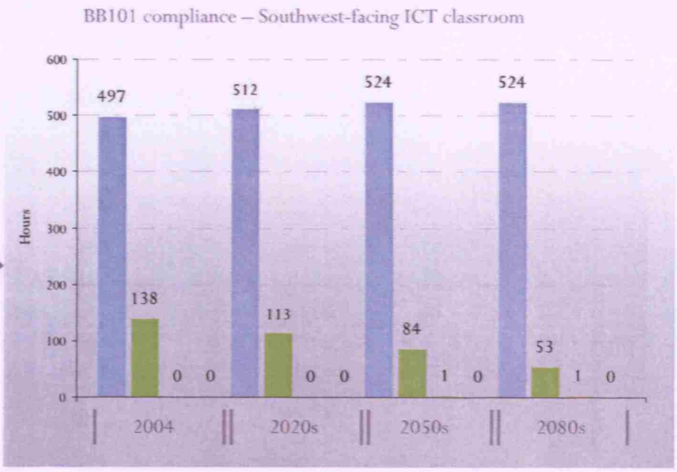


Figure 4-54

BB101 compliance under simulated ventilation strategy
20≤T(°C)≤25
ΔT(°C)≥5
T(°C)≥28
T(°C)≥32

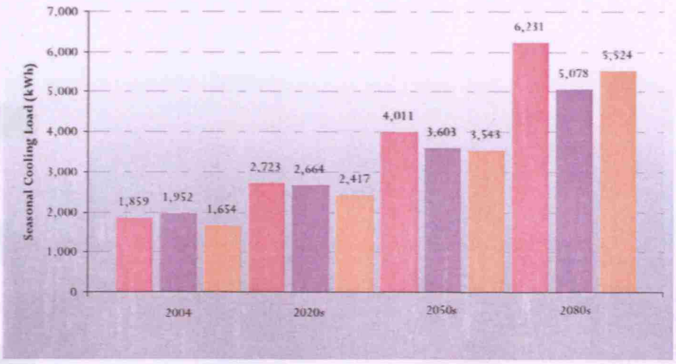


Figure 4-55

Seasonal Cooling Load profile

GF northeast-facing classroom
1F southwest-facing ICT room
1F southwest-facing classroom

In order to illustrate the effect of full air conditioning, it is worth comparing this load profile to that of the Strategy B 'comfort cooling' adaptation strategy.

CHAPTER FIVE
Discussion

5

In this study, three newly-built schools were assessed, using thermal simulation, for the resilience of their environmental and ventilation strategies in providing thermal comfort to occupants and limiting summertime overheating, as outlined by the criteria stated in *Building Bulletin 101*.

Haverstock School in Camden provided ventilation naturally through the use of user-controlled apertures as well as a 'Monodraught' windcatcher system. St Mary Magdalene Academy employed a zonal mixed-mode strategy where classrooms were also naturally ventilated utilising localised stack effect through double-opening single-sided apertures. Paddington Academy utilised a fan-driven low-pressure ventilation system from a ground-coupled subsurface source that supplied air to classrooms and was expelled to low-pressure circulation areas through high-level vents. In addition, all schools employed some means of passive design to minimise energy consumption and their associated carbon footprint.

5.1 Haverstock School

Overheating performance matrix

Figure 5-1

Performance summary for the three classrooms simulated for Haverstock under three ventilation strategies

Haverstock School				
	2004	2020s	2050s	2080s
Strategy A	FAIL	FAIL	FAIL	FAIL
Strategy A	FAIL	FAIL	FAIL	FAIL
Strategy A	FAIL	FAIL	FAIL	FAIL
Strategy B	FAIL	FAIL	FAIL	FAIL
Strategy B	FAIL	FAIL	FAIL	FAIL
Strategy B	FAIL	FAIL	FAIL	FAIL
Strategy C	FAIL	FAIL	FAIL	FAIL
Strategy C	FAIL	FAIL	FAIL	FAIL
Strategy C	FAIL	FAIL	FAIL	FAIL

PASS* indicates a Pass when working in conjunction with the designed ventilation strategy, or because of all-air conditioning

PASS indicates that two of the three BB101 overheating criteria have been met to within a 3.5% tolerance for T≥28ºC (i.e. 138 hours instead of 120 are allowed to overheat) if T<32ºC or a 1% tolerance for T≥32ºC

JUST FAIL indicates that the T≥28ºC criteria has been breached by between 3.5 and 5%, or the T≥32ºC has been breached by between 1 and 2%

Resilience of designed ventilation strategy

From the simulation results obtained, all schools suffered overheating to some extent. With respect to Haverstock School, the designed ventilation strategy was insufficient in the present day to prevent summertime overheating with the north- and south-facing classrooms performing especially poorly with approximately 200 hours forecast of temperatures exceeding 32°C. This was complemented with especially high mean temperatures of 30.8°C, peaking at a maximum of 37.3°C during certain hours of summer. By comparison, the southwest-facing ICT room which was also naturally ventilated, where one would expect significantly more overheating to occur, in fact performed slightly better with only 124 hours of temperatures above BB101's 'never-exceed' temperature of 32°C. Simultaneously, 110 hours of what this study defined to be thermal comfort, 20 to 25°C, were experienced in the ICT room compared with only 86 and 88 hours in the south- and north-facing classrooms respectively.

Furthermore, the effect of a warming climate on the Haverstock School worsened summertime thermal performance, although the increase in the number of hours of thermal discomfort did not rise in proportion with the scaling factors of the UKCIP02 'medium-high' warming scenario. However, on close examination of the performance data in Table 4-1, an indication of the performance of the building envelope can be determined from noticing that 493 of a possible 524 hours during the occupied summer season experienced an internal-external temperature difference of more than 5°C. This suggests that the envelope was so efficient in preventing heat loss that, combined with a 0.5 ach infiltration rate, temperatures were consistently above 28°C. So, when the same categories of number of hours above 28°C and 32°C were applied to the warming 2020s, 2050s and 2080s warming scenarios, the number of hours of overheating were saturated at between 60 and 95%. A fairer depiction of overheating would involve presenting the results at higher temperatures; this would show the rising of the peak temperatures in accordance with the warming scenarios.

Adaptation strategies

Remediation strategies for Haverstock School built upon the studies conducted by *Mavrogianni* (2007) were devised to limit summertime overheating. In Strategy A, this involved the simulation of double-opening windows to generate a localised stack effect which, it was theorised, would convect internal heat gains away from the working plane. The aperture was simulated to be automatically controlled; beginning to open at 19°C and fully opened when the internal temperature reached 21°C. With a classroom depth of 2.15H, which is less than the 5H value prescribed by *CIBSE AM10* (2005), it was supposed that this strategy would provide significantly better thermal performance across all classrooms. However, overheating was only noticeably reduced in the southwest-facing ICT room where performance was improved by 60% in the 2020s, 50% in the 2050s and just under 40% by the 2080s. These improvement factors are broadly consistent with the proportions of the theoretical maximum cooling capacities for localised stack ventilation (see Table 3-15) which suggested a doubling in the maximum cooling capacity by simply adding a low-level inlet.

Improvement in the overheating performance of the southwest-facing ICT room could be explained by that fact that the room was designed with higher ceilings in anticipation of convecting heat gains from computing equipment to above the occupant zone. Since stack ventilation is dependent on the height between the openings (see Equation 3-2), the volume flow rate was increased to a greater extent than in the classrooms which had a height of only 2.7m.

This same reason can be shown to explain the performance of Strategy B, which simulated a side-hung window to increase ventilation. Noticeable improvement was only observed in the southwest-facing ICT room where overheating above 32°C was simulated to be reduced by 37% in the 2020s, 60% in the 2050s and 70% in the 2080s upon the designed ventilation strategy. However, as can be seen, overheating still occurred to a great extent, demonstrating non-compliance with BB101.

Summary

Overall, Haverstock School suffered from overheating under all strategies in all time periods due to four identifiable reasons:

- Highly insulative building envelope
- Low-ceiling heights
- High occupant density
- Poor window design

In Haverstock School, while the insulative envelope may facilitate passive warming during colder seasons, it performs poorly in summer to the extent that a warming climate compounds the scale of overheating. Furthermore, where ceiling levels were higher, such as in the southwest-facing ICT room, performance improvements to the ventilation strategy became effective. Moreover, the high occupant density (1.3-1.6 persons per square metre) that was modelled became a crucial factor in the avoidance of overheating – and again, improvements to aperture configuration became more pronounced in the ICT room because of the relatively lower occupant density.

5.2 St Mary Magdalene Academy

Overheating performance matrix

Figure 5-2

Performance summary for the two classrooms simulated for St Mary Magdalene under five ventilation strategies

St Mary Magdalene Academy				
	2004	2020s	2050s	2080s
Strategy A	PASS	FAIL	FAIL	FAIL
Strategy A	PASS	FAIL	FAIL	FAIL
Strategy B	PASS	PASS	FAIL	FAIL
Strategy B	PASS	JUST FAIL	FAIL	FAIL
Strategy C	PASS	JUST FAIL	FAIL	FAIL
Strategy C	PASS	PASS	FAIL	FAIL
Strategy D	PASS	PASS	FAIL	FAIL
Strategy D	PASS	JUST FAIL	FAIL	FAIL
Strategy E	PASS	PASS	JUST FAIL	FAIL
Strategy E	PASS	PASS	JUST FAIL	FAIL

PASS* indicates a Pass when working in conjunction with the designed ventilation strategy, or because of all-air conditioning

PASS indicates that two of the three BB101 overheating criteria have been met to within a 3.5% tolerance for T≥28ºC (i.e. 138 hours instead of 120 are allowed to overheat) if T<32ºC or a 1% tolerance for T≥32ºC

JUST FAIL indicates that the T≥28ºC criteria has been breached by between 3.5 and 5%, or the T≥32ºC has been breached by between 1 and 2%

Resilience of designed ventilation strategy

In contrast to Haverstock School, St Mary Magdalene Academy's designed ventilation strategy of double-opening apertures achieved good summertime thermal performance under the present-day (DSY2004) climate scenario; only one hour above 32°C was experienced and hours above 28°C were below that prescribed by BB101. However, St Mary Magdalene Academy also experienced a significant number of hours for which the internal-external temperature difference exceeded 5°C. In addition, the designed ventilation strategy was found to provide good thermally comfortable conditions for 45-48% of the summertime occupied hours, with maximum temperatures reaching only 32.8°C. The warming scenarios then projected worsening performance for the designed ventilation strategy with the maximum temperatures forecast to reach 37°C by the 2080s and with an increase in mean temperatures from 24.6°C in 2004 to 29.2°C by the 2080s. In addition, it was shown that overheating would become more acute with 146 hours of temperatures above 32°C in south-facing classrooms and 129 hours in north-facing classrooms compared to 1 hour in 2004.

Adaptation strategies

Several adaptation strategies were investigated for the potential of reducing future summertime overheating. These represented different principles of ventilation, with wind-driven single-sided, cross flow, and split-duct ventilation systems simulated. For Strategy B, the employment of a side-hung aperture to facilitate greater air ingress, theory seemed to corroborate with the performance data; 34% increase in cooling capacity above the designed ventilation strategy was predicted, and similar proportions for the reduction of number of hours of overheating were observed in south-facing classrooms. In the 2020s scenario, a 32% reduction in the number of hours above 28°C was observed, and just under 30% for the 2050s and 2080s. For north-facing classrooms, the adaptation strategy was less effective with an average 24% reduction in hours of overheating upon the designed ventilation strategy. This could be attributable to the lower-speed and less-frequent winds incident on the north façade which, from Equation 3-1, can be seen to influence the volumetric flow rate of wind-driven ventilation.

Strategy C was a variation of Strategy B insofar as the principle of ventilations again depended on wind-forcing. However, this was intended to be an approximation of the effect of vertical louvred windows so as to act as windcatchers in steering the incident air stream into the classrooms (whereas only the orthogonal component of winds at non-90° angles would contribute to the volumetric flow rate). However, user-controlled variable-geometry vertical louvres were not modelled due to the limitations of the software used. The result was merely a larger capacity factor so as to represent an opening of 80% of the total openable area. Results yielded showed an improved performance over the designed ventilation strategy (A), as well as Strategy B, with resilience till the 2050s timeframe when the number of hours above 28°C exceed 120, and the number of hours above 32°C start to become significant (representing 2.5% and 3.2% of summertime occupied hours for south- and north-facing classrooms respectively).

The classrooms at St Mary Magdalene Academy were modelled with a 1:1.92 (height to depth) aspect ratio – within the suggested dept of W≤5H to facilitate cross ventilation. Adaptation Strategy D was therefore a simulation with a smaller lower-hung opening to allow air intake and high-level wall-mounted vents to facilitate extract which were sized to create a mass-flow balance in the classrooms. The results yielded very similar numerical values to that attained by Strategy C, with design resilience until the 2050s by which time a maximum of 4% of occupied hours are at temperatures above 32°C but temperatures above 28°C occur almost one third of the time. The benefits of this strategy as applied to St Mary Magdalene Academy are that the classrooms are relatively narrow plan, and arranged in such a way (almost radially, around a central atrium) that all are exposed to wind forces that correspond to high pressure coefficient differences between the windward and leeward sides. In modelling the strategy, a ΔC_p of 0.51 was used to represent wind traversing urban terrain on the windward façade, and still air on the leeward side of the room. The efficacy of this strategy is noticeable in that the same reduction in overheating as Strategy C is achieved yet with a smaller opening area, thereby reducing occupant discomfort from draughts where sensitivity is such that a 0.25m/s wind gives the sensation of a 1°C reduction in temperature (*CIBSE AM13*, 2005).

Adaptation Strategy E hypothesised the operation of a split-duct system to facilitate the intake of cooler air deeper into the classrooms as well as provide a point of cross-ventilative heat extract, taking into account of the convection of heat gains from the working plane. The adaptation performed better than the others as

- A 1°C reduction in overall mean temperature upon the designed ventilation strategy was achieved
- 259 out of 524 hours during the occupied summer period were in thermal comfort
- The overheating criteria, with the exception of internal-external temperature difference not exceeding 5°C, was met until the 2080s
- In the 2080s time period, upto 27% of occupied hours remain in thermal comfort with 13% of occupied hours exceeding 32°C

Summary

St Mary Magdalene Academy benefits from good passive design, such as the provision of brise-soleil for reduction of solar gains, high ceilings to allow warm air stratification above head height, as well as reasonable occupant densities of 1.9 square metres per occupant. Furthermore, the designed ventilation strategy maintains effectiveness until the 2020s. Beyond this, various adaptation strategies will present themselves for implementation such as side-hung or vertical louvred windows, which are projected to maintain resiliency (based on T≥32°C for less than

4% of the time) until the 2080s time period, although overheating beyond the criteria specified by BB101 will occur before this time. However, it may be possible to forgo Strategies B and C, which have disadvantages in slightly more capital cost, as well as occupant discomfort due to draughts (vertically louvred windows inherently suffer from large air infiltration due to lack of air tightness), in favour of facilitating cross-ventilation in the classrooms. However, the best-performing adaptation strategy is the split-duct ventilator which defers the problem of classroom overheating until the 2050s at the earliest, and only significant contravention of the BB101 overheating criteria in the 2080s.

5.3 Paddington Academy

Overheating performance matrix

Figure 5-3

Performance summary for the three classrooms simulated for Paddington Academy under five ventilation strategies

Paddington Academy				
	2004	2020s	2050s	2080s
Strategy A	PASS	PASS	JUST FAIL	FAIL
Strategy A	PASS	FAIL	FAIL	FAIL
Strategy A	PASS	PASS	FAIL	FAIL
Strategy B	PASS*	PASS*	PASS*	PASS*
Strategy B	PASS*	PASS*	PASS*	PASS*
Strategy B	PASS*	PASS*	PASS*	PASS*
Strategy C	PASS	PASS	PASS	FAIL
Strategy C	PASS	JUST FAIL	FAIL	FAIL
Strategy C	PASS	PASS	FAIL	FAIL
Strategy D	PASS	PASS	PASS	JUST FAIL
Strategy D	PASS	PASS	PASS	PASS
Strategy D	PASS	PASS	FAIL	FAIL
Strategy E	PASS*	PASS*	PASS*	PASS*
Strategy E	PASS*	PASS*	PASS*	PASS*
Strategy E	PASS*	PASS*	PASS*	PASS*

PASS* indicates a Pass when working in conjunction with the designed ventilation strategy, or because of all-air conditioning

PASS indicates that two of the three BB101 overheating criteria have been met to within a 3.5% tolerance for T≥28ºC (i.e. 138 hours instead of 120 are allowed to overheat) if T<32ºC or a 1% tolerance for T≥32ºC

JUST FAIL indicates that the T≥28ºC criteria has been breached by between 3.5 and 5%, or the T≥32ºC has been breached by between 1 and 2%

Resilience of designed ventilation strategy

Paddington Academy proved a difficult building upon which to devise passive overheating remediation strategies for because of its designed mechanical ventilation system which, again despite occurrences of internal-external temperature differences greater than 5°C, proved effective in preventing incidences of high internal temperatures. Moreover, the designed ventilation strategy was projected to be effective in doing this until the 2080s, by which time between 4.8% and 11% of occupied hours could be expected to be above 32°C. However, the caveat in this model is that the simulations were based on the *peak* volumetric air movement from the ground-coupled undercroft to the classrooms of $0.45m^3/s$ (corresponding to 0.45m/s for a 4m by 0.25m duct) which contravenes ISO7730 comfort guidelines for air speed in mechanically ventilated rooms.

In adaptation Strategy B, the effect of comfort cooling was modelled using thermostat settings to control the temperature between 28°C and 32°C. However, the limitation in this is that because of the closeness of control of the strategy, the efficacy of it can only be assessed by evaluation of the cooling loads necessary to maintain the designated operating temperature. In absence of any data on the loads of the designed ventilation strategy, the comparison of the effect of comfort cooling on the designed ventilation is therefore academic. However, from the seasonal loads profile obtained for the Strategy B simulation (see Figure 4-42), it can be seen that by the 2080s, a significant amount of energy, averaging 2,791kWh, will be required to maintain temperatures of between 28 and 32°C. An approximate estimate of the energy consumption of the designed ventilation strategy, taking m = mass flow rate of inlet air 0.54kg/s (peak), c = specific heat capacity of air 1.012kJ/kgK, and ΔT = inlet air-room temperature gradient assumed to be approximately 8K, we obtain from $q = mc\Delta T$, a seasonal cooling load (based on 524 hours of summertime occupied operation) of 2,291kWh. Subtracting from 2,791kWh gives an indication of the cooling loads necessary to provide comfort cooling.

Strategy C hypothesises the increase in the potential for night cooling by use of double-opening windows. The effect of this on the occurrence of overheating is palpable; again, with the exception of the criteria for $\Delta T \leq 5°C$, guidelines for temperature exceedances above 28°C and 32°C are satisfied until the 2080s period in ground floor northeast-facing classrooms, although for southwest-facing classrooms, including the ICT room, this requires earlier intervention. The southwest-facing ICT room suffers especially with 179 hours of temperatures greater than 28°C during the 2050s. Decrease in the efficacy of night cooling with a warming climate is also attributable to a smaller diurnal range observed in the graphs showing performance during the warmest week 13 to 20 June (Figure 4-44).

Strategy D simulated the operation of a split-duct type system which proved effective in reducing mean temperatures as well as was forecast to reduce peak temperatures by 3.2°C in the 2080s time period. The split-duct system demonstrated that such a passive system could work in conjunction with the low-pressure mechanically ventilated system, in providing thermal comfort for 52%

occupied hours in 2004, 50% during the 2020s, and 38% during the 2050s. A point to note is that an effective building management system would be needed for close coupling of fan-assisted supply and the monitoring of the passive extract to ensure that the fans are not unnecessarily overpowered when the split-duct would be adequate at providing some proportion of the cooling capacity for the classroom.

Strategy E was a variation of Strategy B in that the indoor temperature was controlled artificially by a thermostat. For the reasons already outlined, the seasonal cooling loads indicate the relative efficiency of the strategy, and as can be seen by the load profile (Figure 4-55), full-air conditioning requires more than double the energy requirement of Strategy B comfort cooling (more than double because comfort cooling is designed to allow the existing ventilation strategy provide most of the cooling capacity, with temperature excesses met by fan coil units or other cooling emitters).

Summary

As a result of the testing of various strategies on Paddington Academy, it can be seen that the designed ventilation strategy will remain resilient in satisfying overheating (absolute temperature exceedance) criteria until the 2050s. In fact, the designed ventilation system is such that the efficiency will improve under a warming scenario as the temperature differential ΔT will increase given the fixed ground temperature of 12-16°C at depths of 1.5m, so it is possible that the data projected in Strategy A could under-represent its actual overheating reduction potential.

5.4 Other Factors Affecting Overheating

Ceiling height

From the analysis of the three schools, various applications of the different principles of ventilation have been applied and tested under different time periods in the UKCIP02 'medium-high' warming scenario. From this, it is evident that inherent design features are as important to the reduction of summertime overheating as the ventilation or aperture strategy. For example, low-ceilings of 2.5m in conjunction with short windows in Haverstock School are not conducive to the operation of stack principles. Where the localised stack effect cannot be suitably implemented, the means of ventilation then becomes dominated by wind-forcing (as $Q_s \rightarrow 0$, $V_T = \sqrt{Q_w^2 + Q_s^2}$ becomes $V_T = Q_w$). This was seen under Strategy C (vertical sash louvres) as applied Haverstock School where little improvement in overheating reduction was made compared to Strategy B.

Building envelope

Furthermore, efficient building envelopes designed under the '*build tight, ventilate right*' ethos have resulted in the compounding of overheating in buildings which experience high densities of internal heat gains anyway. This may also have been seen in Haverstock School where classrooms on all facades retain heat with little improvement in the summertime thermal performance under different overheating reduction strategies.

As a consequence of airtight and thermally efficient building envelopes, all schools under all design conditions failed to meet the BB101 standards for limiting internal-external temperature difference to below 5°C during occupied hours. So while some scenarios performed better in reducing the absolute peak temperatures (and still therefore passed the overheating test), they still failed when assessed against the entire BB101 criteria. It seems a paradox that building designers must be expected to satisfy this criteria (that ΔT≤5°C) whilst also practising building 'tight' for the present heating-dominated climate. Therefore, in order to pass the BB101 overheating test, designers may seek to reduce the absolute internal temperature, irrespective of the external climate, whether measured as a dry-bulb temperature or as a mean radiant temperature. If it is the latter, then building designers may favour heavyweight thermal mass materials in the future to lower mean radiant temperatures, and place a lesser effect of dispelling heat gains through ventilation.

Night ventilation

The use of heavyweight thermal mass could be further developed upon by using night ventilation to pre-cool the structure. Although all schools in this study had some limited capacity for night cooling built into the design, the potential for this was explored further by assessing night cooling/purge ventilation with larger openable areas to facilitate a greater number of room air changes. This was demonstrated under Strategy C for Paddington Academy where a marked decrease in overheating was achieved by increasing the window area open during unoccupied hours. The benefits of night cooling are corroborated by Kolokotroni *et al.* (2001) showing significant daytime temperature reduction with exposed thermal mass coupled to nocturnal air change rates.

However, the warming scenarios also indicate a reduction in the diurnal temperature range, as shown by the warmest week and hottest day graphs. The implications are that the cooling capacity of night time air will be reduced in an increasingly warmer climate. By the 2080s, this will be especially pronounced as, based on Strategy C applied to northeast-facing classrooms at Paddington Academy, only a 13% reduction in overheating will be attributable to night ventilation, compared with 29% in the 2050s, 51% in the 2020s, and 65% if this were applied in the present day.

CHAPTER SIX
Conclusions

6

Current predictions suggest that the United Kingdom is likely to become a cooling-dominated climate which will test the mettle of the current stock of non-domestic buildings and pushing them to perform beyond their limits in the provision of thermal comfort for their occupants. Within this context, the *Building Schools for the Future* (BSF) programme seeks to capitalise upon this two- or three-generational opportunity to foster social environments conducive to learning through architectural statements. In addition, BSF seeks to instil in the new generation of students the importance of sustainable construction and 'green' building design. For architects, engineers and consultants, this project offers an opportunity to experiment with and hone the skills pertaining to energy-efficient, low-carbon school design that will in the future, need to be applied across the entire building stock in order to meet global commitments for the reduction in high greenhouse gas emissions that are a result of wasteful energy consumption. As part of sustainable school design, designers must seek to create thermally comfortable internal environments for as little energy expenditure as possible. In doing so, ventilation of school buildings forms a crucial part of this strategy, informing spatial planning, construction details, and user operation.

This study has aimed to identify the different ventilation strategies employed in the provision of low-energy thermal comfort and has sought to assess its efficiencies in doing so, under the context of the projection of increased temperatures.

The key outcomes of this study has been that firstly, it is difficult to prescribe a blanket ventilation strategy for every school under the BSF programme, as site context should inform the design through microclimate analysis and site pollution loci. That said, certain features conducive to good environmental design *should* be prescribed – such as avoidance of direct solar gains, and, importantly, classroom geometry. It was observed that in Haverstock School, low ceilings and lightweight, unexposed thermal mass were not conducive to effective ventilation, despite being constructed with a thermally efficient envelope. When designing adaptation strategies for overheating remediation, it proved difficult as classroom geometry did not lend itself to the physical principles of various ventilation types.

Secondly, although a ventilation strategy is highly context-specific, some types more than others proved to offer better control of climate to avoid summertime overheating; in St Mary Magdalene Academy, the designed ventilation strategy of double-openings proved effective until the 2020s. Beyond this, the increased temperatures had an effect such that the ventilative capacity of localised stack effect performed poorly. Adaptations to the window design projected that, if high-level vents were installed on the leeward side of the classroom to facilitate cross ventilation, summertime overheating could be prevented until the 2080s. This was corroborated with evidence from Paddington Academy, which although supplied air mechanically, employed cross ventilation and achieved similar results pertaining to the avoidance of summertime overheating. Split-duct type systems were assessed and proved to provide a similar efficacy to cross ventilation in the reduction of summertime overheating.

Both St Mary Magdalene Academy and Paddington Academy benefited from the use of exposed thermal mass applied to ceilings so as to act as heat sinks during summer nights. The effect of night ventilation was seen in Paddington Academy with a larger area of window opened overnight. However, it was determined that by the 2080s, night-ventilation will have considerably reduced effects due to a smaller diurnal temperature range and so larger areas of openable windows may be necessary by this time to create the air change rates required for pre-cooling of the structure. This obviously has issues associated with it, but these are outside the scope of this study.

Where cross-ventilation or split-duct type systems do not create any significant reduction in summertime overheating, it was determined that comfort cooling could be applied at temperatures beyond which natural or low-energy mechanical ventilation could provide. This was found to be considerably less energy intensive than all-air conditioning, and ventilated with the provision of adequate fresh air as well as provided for the expulsion of heat gains.

Thirdly, this study highlighted the necessity for thermal modelling as part of the building design process, so as to identify not only areas, but also times (based on forecast weather data) which affected the performance of the building. The modelling needs to go beyond that which is provided by thermal analysis and take a holistic approach to more closely represent occupant and systems behaviour.

It is hoped that these lessons learned early on in the Building Schools for the Future programme will help inform stakeholders to provide evidence-based design strategies so as to create a generation of schools that are exemplars of sustainability.

References

Apte, M. G., and Fisk, J. M. (2002) *Association between Indoor (CO_2) Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 BASE Study Data* (LBNL 44385), Indoor Air 10: 246-257

Bako-Biro, Wargocki, P., Weschler, C. J., Fanger, P. O., (2004) *Effects of pollution from Personal Computers on Perceived Air Quality, SBS Symptoms and Productivity in Offices*, Indoor Air 2004, 14:178-187

Bassett and Gibson (1999) *AIVC 20th Conference and Indoor Air 99*, the 8th International Conference on Indoor Air Quality and Climate, 4, Edinburgh

BB101 (2006) *Building Bulletin 101 Ventilation of School Buildings*, v1.4, Department for Children, Schools and Families (formerly DfES)

Brennan, T., Clarkin, M., *et al.*, (1991). *School Buildings with Air Exchange Rates that o not meet Minimum Professional Guidelines or Codes and Implications for Radon Control*, Proceedings of ASHRAE IAQ 91 Healthy Buildings, Atlanta GA, ASHRAE 228-229

Buro Happold (2005) *Stage D Report: Paddington Academy*, Buro Happold

Buro Happold (2006) *Stage D Report: St Mary Magdalene Academy*, Buro Happold

CIBSE Guide A (Braham, D., *et al.*), (2006) *CIBSE Guide A: Environmental Design*, Chartered Institute of Building Services Engineers, London

CIBSE AM13 (Jaunsenz, D., *et al.*), (2000) *CIBSE AM13: Mixed Mode Ventilation*, Chartered Institute of Building Service Engineers London

CIBSE TM36 (Moss, B., *et al.*), (2005) CIBSE TM36: *Climate Change and the Indoor Environment*, Chartered Institute of Building Service Engineers London

CIBSE AM10 (Moss, B., *et al.*), (2005) *CIBSE AM10: Natural Ventilation in Non-Domestic Buildings*, Chartered Institute of Building Service Engineers London

Climate Change Bill (2006) *Climate Change and Sustainable Energy Act 2006*, Chapter 19, The Stationery Office, London

Coley, D.A., Beisteiner, A., (2002) *Carbon Dioxide Levels and Ventilation Rates in Schools*, International Journal of Ventilation, 1:1

Department of Trade and Industry (2005) *DTI Energy Trends*, The Stationery Office, London

Department for Environment, Food and Rural Affairs (2007) *UK Climate Change Bill*, **CM7040**, The Stationery Office, London

Directive 2002/91/EC (2002) *Energy Performance in* Buildings, European Parliament, Brussels

Griffiths and Eftekhari (2008) *Control of CO_2 in a Naturally Ventilated Classroom*, Energy and Buildings **40**:556-560

Haw, N., (2002) *Impact of Climate Change on Energy Consumption of UK Dwellings*, University College London, MSc Dissertation, London

House of Commons Education and Skills Committee (2007) *Sustainable Schools: Are We Building Schools For The Future? Seventh Report of Session 2006-7*, Volume 1, The Stationery Office HC140-I, London

IPCC (1998) *Special Report on Emissions Scenarios*, Intergovernmental Panel on Climate Change

International Organisation for Standardisation ISO Standard 7730 (1994) *Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort*, Geneva

Kolokotroni, M., Perera, M. D. A. E. S., Azzi, D., Virk, G.S., (2001) An *Investigation of Passive Ventilation Cooling and Control Strategies for an Educational Building*, Applied Thermal Engineering **21**:183-199

Kyoto Protocol (1997) *United Nations Framework Convention on Climate Change*

McIntyre, D. A., (1980) *Indoor Climate*, London **Applied Science Publishers**

Mavrogianni, A., (2007) *Impact Assessment of Climate Change on Thermal Comfort in a Naturally Ventilated School*, University College London, MSc Dissertation, London

Mendell, M. J., and Heath, G. A., (2005). *Do Indoor Pollutants and Thermal Conditions in Schools Influence Student Performance? A Critical Review of the Literature*, Indoor Air **15**:27-52

Mumovic, D., Davies, M., Ridley, I., Oreszczyn, T., (2006) *Ventilation Measurements – Season 1*, Ventilation in Schools – Project Reference Number: C1 71/6/37 cc2505

ODPM (2006) *Approved Document L2A: Conservation of Fuel and Power in New Buildings other than Dwellings*, Office of the Deputy Prime Minister

ODPM (2006) *Approved Document F: Means of Ventilation*, Office of the Deputy Prime Minister

Pegg, I., Cripps, A., Kolokotroni, M., (2005) *Cooling Season Post-Occupancy Evaluation of a Low Energy Complex School*, International Conference 'Passive and Low Energy Cooling for the Built Environment', Santorini Greece 1083-1089

Potting, J., Van de Sandt, P., ter Haar, I Romeny-Wacher., Brunekreef, B., Bolesij, S. M., (1987) *Health Complaints, CO_2 Levels and Indoor Climate in Dutch Schools,* Indoor Air 87, Proceediungs of the 4th International Conference on Indoor Air Quality and Climate, Institute of Water, Soil and Air Hygiene, Berlin, Vol 3:582-586

Santamouris, M., Asimakopoulos, D., (1996) *Passive Cooling of Buildings*, **James & James Science Publishers Ltd**

Santamouris, M., (1993) 'NORMA – *A Method to Calculate the Thermal Performance of Passively Cooled Buildings*, Cooling Load of Buildings, Vol 5:1.1, School of Architecture, University College Dublin, Dublin, Ireland

Seppanen, O. A., Fisk, W. J., and Mendell, M.J., (1999) *Assocation of Ventilation Rates and CO_2 Concentrations with Health and Other Responses in Commercial and Institutional Buildings,* Indoor Air 9:226-252

The Education (School Premises) Regulation (1999), *Statutory Instrument No 2 1999*, Queen's Printer's Acts of Parliament

Wargocki,P., and Wyon, D. P., (2007) *The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children* HVAC&R Research, 13(2):193-220

15000Btu Unionaire http://www.ecoairandwater.com/store/15000-btu-unionaire-ductless-air-conditioner-heat-pump.html [Retrieved 27th August 2008]

BNF (2008) *British National Formulary Body Surface Area Calculator* (web) [Retrieved 19th August 2008]

London Air (2008) *Nitrogen Dioxide Concentration*,
http://www.londonair.org.uk/london/asp/advgraphssiteplot.asp?CBXSpecies3=NO2&day1=1&month1=jan&year1=2007&day2=1&month2=jan&year2=2008&period=15min&Submit=plot+the+graph&site=KC1&res=6, [Retrieved 2nd August 2008]

McQuay S06
http://www.mcquayservice.com/mcquaybiz/literature/lit_at_fc/PhysicalData/PdataFanCoilsLargeCapacity.pdf [Retrieved 27th August 2008]